

Evaluation of Natural Attenuation and Biodegradation Potential of Chlorinated Aliphatic Hydrocarbon Compounds in Groundwater at Rocky Flats

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Rocky Flats Environmental Technology Site Golden, Colorado

March 2004





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Rocky Flats Environmental Technology Site Golden, Colorado

Kaiser-Hill, L.L.C.

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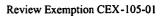
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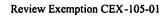


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#### **EXECUTIVE SUMMARY**

This report presents evidence of the extent of natural attenuation processes reducing the concentrations of chlorinated aliphatic hydrocarbons (CAHs) detected in groundwater at the Rocky Flats Environmental Technology Site (RFETS or Site). CAH compounds detected in groundwater at the RFETS are sourced from past chlorinated solvent spills that occurred at the Site while it was operating. Chlorinated solvents known to have been used at RFETS include carbon tetrachloride (CT), tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (1,1,1-TCA), chloroform (CF), and methylene chloride (MC). This evaluation uses available groundwater quality data to estimate the rates of natural attenuation for these constituents by calculating several types of degradation rate constants. This report also uses a number of geochemical lines of evidence to document the extent of biodegradation at RFETS.

A site-specific conceptual model was developed for natural attenuation processes that may occur at the RFETS. This model views biodegradation as occurring within small "islands" where anoxic conditions can be locally maintained to support reductive dechlorination, the principal mechanism for CAH biodegradation, of relatively oxidized CAHs like CT, PCE, and TCE. These "islands" of biodegradation are surrounded by a "sea" of oxidizing groundwater that probably does not support reductive dechlorination. The mean concentration of dissolved oxygen (DO) in shallow groundwater at RFETS is relatively high at 5.7 mg/L. Reductive dechlorination would most likely be eliminated under these oxidizing conditions, although vinyl chloride may be rapidly oxidized. Under oxidizing or reducing conditions, 1,1,1-TCA undergoes rapid hydrolysis (half-life 0.5 to 1.7 years) to acetic acid. Thus, 1,1,1-TCA has the best chance for the most rapid natural attenuation of the primary solvents used at the RFETS.

Fuel spills resulted in benzene, toluene, ethyl benzene, and xylenes (BTEX) spatially associated with some CAH plumes. These constituents, if present in groundwater, provide an organic substrate for bacterial growth and help produce locally anoxic conditions at the islands through microbial respiration. The lathe coolant used at the RFETS should be particularly amenable to biodegradation since the hydraulic oils in the coolant would be a suitable substrate for bacterial growth resulting in reducing conditions that support CAH reductive dechlorination.

The CAHs undergoing natural attenuation in groundwater at the RFETS have been evaluated using various lines of evidence suggested in the technical literature. These lines of evidence include estimation of biodegradation rate constants, bulk attenuation rate constants, point attenuation rate constants, and overall mass removal of CAHs from groundwater.

Several hundred graphs and maps were prepared to interpret water quality data to:

• Determine attenuation rate constants;



- Interpret redox environments suitable for biodegradation;
- Visualize the extent of natural attenuation of CAHs through time; and
- Interpret the attenuation of CAH concentrations along groundwater flowpaths.

A ranking system based on Wiedemeier scores (Wiedemeier et al., 1999) was used as a screening tool to quickly assess the occurrence and extent of biodegradation that may be occurring at the Site. This screening system is based on the concept that biodegradation will cause predictable changes in groundwater chemistry (EPA, 1998). If most of the relevant water quality parameters have been measured, then their concentrations may be compared against this scoring system, which assigns points (-3 to +3) to individual parameters. The points for all parameters are summed to produce a Wiedemeier score for each well.

Groundwater field parameters and analytical concentrations were used to develop a Wiedemeier score at wells that had sufficient data. Wiedemeier scores for 579 monitoring wells at RFETS ranged from a minimum of -3 points to a maximum of +22 points. The mean score was 3 points with a standard deviation of 3.4 points. Cumulative frequency data indicate that 78% of the wells at RFETS have groundwater scores below 6 points indicating inadequate to no evidence of biodegradation.

Based on presently available data, well 33502 is the only well at RFETS exhibiting strong evidence of biodegradation based on a maximum score of 22. Well 33502 is located under Sage Avenue just north of B335. Well 33502 has elevated vinyl chloride (VC) concentrations (1,200  $\mu$ g/L) in February, 2003 that exceed the Tier I groundwater action level of 200  $\mu$ g/L.

A second monitoring location, well 1986, had adequate evidence of biodegradation with a maximum score of 19. Well 1986 is located about 1,500 feet northeast of well 33502. All other wells (99.2% cumulative frequency) had scores less than 15, indicating lesser degrees of evidence. These wells included:

- 125 wells with limited evidence of biodegradation (6 to 14 points);
- 349 wells with inadequate evidence of biodegradation (1 to 5 points); and
- Hundreds of wells and drains with no positive evidence of biodegradation.

Approximately 170 graphs were prepared where the natural log of contaminant concentration (ln C) was plotted against contaminant migration distance (D) using data from wells located along a groundwater flowpath from a CAH source area. Each chart shows the trend in detected concentrations of a single CAH at multiple wells located along the flowpath during a restricted time period.

These ln C versus D plots were prepared to determine bulk attenuation rate constants  $(K_b)$  for individual CAHs in each of seven areas of interest in or near the Industrial Area (IA). A  $K_b$  value is a composite rate

constant for all natural attenuation processes that may be operating at a site. Bulk attenuation rate constants are useful for two purposes. First, they can be used to predict the future extent, or size of a plume, and whether it should grow, shrink, or remain at steady-state. Second, for steady-state plumes, the same data used to compute  $K_b$  values can be used to estimate biodegradation rate constants.

Natural attenuation processes are widely believed to decrease contaminant concentrations during contaminant migration along a groundwater flowpath from a contaminant source area. Considering the RFETS results, 103 of the ln C versus D plots had regression lines with negative slopes (positive K<sub>b</sub> rates) indicating that the concentrations of CAHs were naturally attenuating during contaminant migration. However, another 64 of the ln C versus D plots exhibited positive slopes (negative K<sub>b</sub> rates) indicating that the concentrations of some contaminants were actually increasing through time in groundwater at RFETS. The most likely explanation is that the plume segments with positive slopes show only the rising limb of increasing daughter product concentrations. If more closely-spaced wells were available along each plumes' flowpath, then the daughter concentrations should peak and then attenuate with distance in accordance with the conceptual model (Figure 3-5).

Plumes that are predicted to shrink are attenuating faster at an average bulk attenuation half-life of 7.5 years. Plumes predicted to grow are attenuating slower with average bulk attenuation half-lives of 19.8 years. The bulk attenuation half-life of steady-state plumes averaged 15.1 years. Using these half lives, a wide range of predicted decay times was found for CAHs in Site groundwater to attenuate below the Tier II groundwater action levels. Estimated decay times ranged from one to more than 1,200 years.

Biodegradation rates were computed for the attenuation of CAHs in groundwater at the RFETS. The calculations were performed using the one-dimensional (1D) method of Buscheck and Alcantar (1995). This method likely overestimates the true biodegradation rate (Zhang and Heathcote, 2003) but is suitable for estimating biodegradation rates. Uncertainty concerning the dimensions and location of contaminant source areas precludes the application of more sophisticated methods.

The Buscheck and Alcantar 1D method requires that a plume be at steady-state during the time period evaluated, otherwise the computed rate constant will be an approximation of the actual biodegradation rate. Thirty-five biodegradation rate constants were computed for plumes of individual CAH compounds that were predicted to be at steady-state. The mean biodegradation half-lives for specific CAH chemicals in groundwater at the RFETS calculated using this method are 1,1-dichloroethane (1,1-DCA) 30.3 years, TCE 22.4 years, 1,1,1-TCA 15.9 years, PCE 10.8 years, cis-1,2-dichloroethene (cis-1,2-DCE) 10.4 years, MC 8.1 years, 1,1-dichloroethene (1,1-DCE) 3.0 years, and CF 0.8 years.

Comparison of CAH biodegradation rates for RFETS with other chlorinated solvent contaminated sites indicates that the RFETS rates are at or near the low end of published biodegradation rate constants. Rate statistics compiled from published field and laboratory biodegradation rate studies (Aronson and Howard, 1997) indicate that the mean biodegradation rates for these other sites are higher. The mean CAH



biodegradation rates at the RFETS are less than 1, except for CF at 2.65 per year. For example, the non-RFETS CF mean biodegradation rate is 29.2 per year, 11 times faster than those calculated for the RFETS. The non-RFETS PCE biodegradation rate is 9.86, about 143 times faster than the mean biodegradation rate at the RFETS. The non-RFETS TCE biodegradation rate is 4.02, about 12 times faster than the RFETS' mean biodegradation rate. Assuming that 1,2-DCA decays at a similar rate to 1,1-DCA, then the non-RFETS mean biodegradation rate is 2.78, about 9 times faster than 1,1-DCA biodegradation rates at RFETS. Comparison of the estimated CT biodegradation rate of 0.163 per year at the RFETS to the non-RFETS rate of 124 per year, indicates that the Site rate is about 760 times less than the non-RFETS sites.

Biodegradation rate constants computed using the 1D method of Buscheck and Alcantar (1995) are believed to overestimate the true rate constant by up to 65% in comparison to a more rigorous 3D method (Zhang and Heathcote, 2003). Thus, the true biodegradation rates at RFETS are likely to be even less than those reported here (Tables 5-6 and 5-7).

Another line of evidence demonstrating CAH natural attenuation in groundwater at RFETS is a decrease in CAH mass over time. The total CAH mass per liter of groundwater was computed for two time periods, 1992-1993 and 2002-2003. Possible seasonal concentration effects were reduced by averaging the CAH concentrations within each two-year period. If natural attenuation is occurring, a large decrease in contaminant mass should be observed between the time periods.

A total of 122 wells had sufficient data to compare the potential CAH mass loss between the two periods. CAH mass decreased during the decade at 91 monitoring wells indicating that natural attenuation is occurring at those wells. The average mass decrease was 14.0 µMoles/L per well. The remaining 31 wells showed no evidence of natural attenuation, but instead showed increases in CAH mass. The average mass increase at these wells was small at 3.5 µMoles/L per well. If the contaminant mass changes at all 122 wells are summed, the net change is an overall loss of 1,169 µMoles, or 9.6 µMoles/L per well. This is evidence that on a site-wide basis, CAH plumes at RFETS are undergoing natural attenuation. The overall mass loss is actually a rate, 9.6 µMoles/L per decade at each well. Therefore, the Site-wide average "mass attenuation rate" for CAHs in groundwater at the Site is 0.96 µMoles/L/yr.—

Ratios of the cis and trans stereoisomers of 1,2-DCE have been used in the published literature as a qualitative indicator of biodegradation. Commercial solvents are a mixture of cis- and trans-1,2-DCE. In contrast, biologic al processes (biodegradation) produce mainly cis-1,2-DCE (EPA, 1998). The cis/trans ratio is typically greater than 25 to 1 in groundwater where biodegradation is actively occurring. The cis/trans ratio was computed for each well and sampling event at the RFETS with detectable isomer concentrations. Although some wells have low ratios, most wells had high ratios between 26 and 684, suggesting that CAH biodegradation is occurring in those areas.



Sampling and analysis of Site groundwater during the Snapshot Sampling Program (completed in August 2003) generated data that provide a current picture (or Snapshot) of the distribution of CAHs in groundwater at the RFETS. This report includes two sets of plume maps based on the Snapshot data that show the spatial distribution of the concentrations of individual CAH compounds in Site groundwater during 2002-2003 relative to Tier I and II groundwater action levels. Snapshot data indicate that six CAH plumes presently occur in groundwater at RFETS at concentrations exceeding Tier I groundwater action levels. These plumes include CT, CF, PCE, TCE, 1,1-DCE, and VC. The word plume in this context, refers to the mapable extent of a single chemical dissolved in groundwater at concentrations greater than the relevant action level, regardless of the number of source areas.

In summary, this report evaluated various lines of geochemical evidence bearing on the extent and rates of natural attenuation processes operating in groundwater at the RFETS. The overall conclusion is that biodegradation of CAHs dissolved in groundwater occurs locally in the IA and East Trenches area. However, the estimated biodegradation rates are very slow, occurring near the low end of the range of rates published for other sites. These low biodegradation rates make it difficult to demonstrate that Monitored Natural Attenuation (MNA) is a practical groundwater remedial option for the RFETS.



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#### **ACRONYMS & TERMS**

Abiotic Used to refer to chemical reactions that occur without the involvement of

microorganisms.

Acetate The anion of the dissociation of acetic acid (CH<sub>3</sub>-COOH). Acetic acid may be

produced in groundwater environments by the hydrolysis of 1,1,1-TCA. Thus,

the acetate ion is a daughter product of the dechlorination of 1,1,1-TCA.

Aerobic An aerobic groundwater environment is one that contains measurable dissolved

oxygen. The usual detection limit is about 0.1 mg/L.

Aliphatic A class of hydrocarbon compounds including the alkane, alkene, and alkyne

families. See also CAH.

Alkalinity Total groundwater alkalinity is the sum of all aqueous chemical species that are

titrateable with strong acid to a pH near 4. In most groundwaters, bicarbonate

ion is the major component of the measured alkalinity.

Alkane A family of open-chain hydrocarbons containing only carbon-carbon single

bonds, e.g. ethane (CH<sub>3</sub>-CH<sub>3</sub>). Cyclic alkanes are not considered in this report.

Alkene A family of open-chain hydrocarbons characterized by one carbon-carbon double

bond, e.g. ethene (CH<sub>2</sub>=CH<sub>2</sub>). Ethene is also called ethylene.

Alkyne A family of open-chain hydrocarbons characterized by one carbon-carbon triple

bond, e.g. acetylene (CH≡CH). Acetylene is also called ethyne.

Anaerobic Describes a geochemical environment in which oxygen is absent (or has a

concentration below the detection limit).

Analyte Any chemical or radionuclide whose concentration or activity in groundwater is

determined in the field or by a laboratory.

Anoxic A synonym for anaerobic.

Aqueous Refers to chemical reactions in water. For example, "aqueous solubility" is the

solubility of a compound in water.

Aquifer Matrix See porous medium.

ASD Kaiser-Hill Analytical Services Division. This group establishes procedures and

contracts that govern the analysis of groundwater samples collected at the



RFETS, and the subsequent verification and validation of the analytical data. ASD is also responsible for entering and maintaining the data in SWD.

B- RFETS building number, e.g., B-771 is Building 771.

Background M2SD Background mean + two standard deviations. These values are calculated on a

site-wide basis for analytes.

Biodegradation Microbiologically-mediated conversion of one compound into another. In the

case of CAHs, successive stages of biodegradation produce progressively simpler, lower molecular weight daughter products (see Decay Chain).

Biodegradation Rate Constant A rate constant that isolates and quantifies the rate at which biodegradation reactions are occurring, exclusive of all other natural attenuation processes, such

as advection, sorption, volatilization, dilution, etc. This report follows standard practice of modeling biodegradation rate constants as a first-order reaction rate process. The biodegradation rate is often designated as lambda,  $\lambda$ . In this report

 $\lambda$  has units of per year.

BTEX Benzene, toluene, ethylbenzene and xylene isomers usually found dissolved in

groundwater contaminated by gasoline spills.

CA Chloroethane, or ethyl chloride, CH<sub>3</sub>-CH<sub>2</sub>Cl, is the daughter product of the

reductive dechlorination of 1.1-DCA, and the second daughter of the 1,1,1-TCA

decay chain. CA in turn decays to ethanol or ethane.

CAH Chlorinated aliphatic hydrocarbon. CAHs relevant to this report include

chlorinated straight-chain members of the alkane and alkene hydrocarbon families of organic compounds. Technically, CAHs also include the alkyne

family.

Carbonic Acid Dissolved carbon dioxide associates with water molecules to form carbonic acid,

H<sub>2</sub>CO<sub>3</sub>, which partially dissociates (depending on the pH) to the ions bicarbonate HCO<sub>3</sub>, and carbonate CO<sub>3</sub>. Bicarbonate is usually the main component of

measured alkalinity in natural groundwaters.

CAS Chemical Abstracts Service assigns a unique number to identify analytes that

may have multiple chemical names. The registry number is called a CAS

Number.

CDPHE Colorado Department of Public Health and Environment

Chloroethanol CH<sub>3</sub>-CHClOH, forms from the aerobic biodegradation of 1,2-DCA.



CF Chloroform, or trichloromethane, CHCl<sub>3</sub>, is the first daughter of the CT decay

series.

cis- Refers to the cis- isomeric configuration of an organic compound.

CLP Contract Laboratory Program (or Procedures) developed by EPA.

CM Chloromethane, or methyl chloride, CH<sub>3</sub>Cl, forms from the dechlorination of

MC, and is the third daughter of the CT decay chain.

COC Contaminant of concern.

CT Carbon tetrachloride, or tetrachloromethane, CCl<sub>4</sub>, is an important solvent used at

the RFETS, and the parent molecule of its decay chain.

D Migration distance of a contaminant carried by groundwater from a source area

downgradient along a flowpath towards its discharge point. D is used as the

parameter on the horizontal axis of many charts included in this report.

Daughter Daughter compounds are formed initially by the degradation of a parent

compound, and then by successive degradation of earlier daughters in a decay chain. Daughters may be referred to by generation as the first daughter, or

second-generation daughter, etc.

D&D Decontamination and decommissioning

DCA Dichloroethanes in general, including: 1,1-DCA and 1,2-DCA. 1,1-DCA is the

more common isomer in the RFETS groundwater and is the first daughter of the

dechlorination of 1,1,1-TCA.

DCE Dichloroethenes in general, including: cis-1,2-dichloroethene (CHCl=CHCl);

trans-1,2-dichloroethene; and 1,1-dichloroethene (CH<sub>2</sub>=CCl<sub>2</sub>). All three DCE isomers are potential first daughters of the dechlorination of TCE. Cis-1,2-DCE is the most abundant daughter produced by biodegradation of TCE, and cis-1,2-DCE is the second daughter of the PCE decay chain. A further complication is

that 1,1-DCE is also a potential first daughter of 1,1,1-TCA.

Decay Chain Several common chlorinated solvents tend to degrade from the parent compound

through a series of progressively less chlorinated daughter compounds. This progression is a type of decay chain analogous to radionuclide decay chains.

Describes chemical reactions in which chlorine atoms are removed from a CAH

molecule.

**DNAPL** 

Dense non-aqueous phase liquid. Refers to halogenated hydrocarbon solvents that are denser than water. DNAPLs like carbon tetrachloride, have a limited solubility in groundwater, and are sometimes found as a separate liquid phase in an aquifer or monitoring well.

DO

Dissolved oxygen concentrations measured in groundwater during sampling.

DOE

United States Department of Energy

**DQA** 

Data Quality Assessment as used in this report focuses on evaluations of the PARCC parameters.

DUP

DUP is a SWD code identifying data describing field duplicate samples. In this report DUP refers to data describing a duplicate groundwater sample collected in the field and associated with a REAL sample.

Ε.

Numbers may be expressed in scientific notation as powers of ten, using E to represent 10 raised to the exponent. For example, 3.14E5 equals 3.14 times 10<sup>5</sup>, or 314,000. In this example, the exponent was 5. Negative exponents are also used to indicate small values.

Eh

The voltage of a groundwater or aqueous chemical solution measured between a platinum electrode and a reference electrode and then related to the standard hydrogen half-cell potential. ORP measurements may be converted to Eh if the type of reference electrode used, its filling solution, and the measurement temperature are known. Eh is theoretically related to the aqueous concentrations or activities of electroactive ions in solution by the Nernst Equation.

**EPA** 

United States Environmental Protection Agency.

Ethane

Ethane (C<sub>2</sub>H<sub>6</sub>) is a daughter of the dechlorination of chloroethane, and is a third daughter of the 1,1,1-TCA decay series.

Ethanol

A two-carbon alcohol, CH<sub>3</sub>-CH<sub>2</sub>OH, produced by the hydrolysis of chloroethane in groundwater.

Ethene

Ethene  $(C_2H_4)$  is usually produced in groundwater by dechlorination of VC. This makes ethene the fourth daughter of PCE decay, or the third daughter of TCE decay. It is also possible for ethene to be produced as a daughter of 1,2-dichloroethane.

**ETPTS** 

East Trenches Plume Treatment System

First-order process

Biodegradation reactions are usually modeled as a first-order decay process. If  $C^{\circ}$  is the initial concentration of a chemical, and t is elapsed time, and k is the first-order rate constant, then the concentration at any time t is,  $C = C^{\circ} e^{-kt}$ .

 $f_{oc}$ 

The fraction of organic carbon by weight in a soil.

GC/MS

An analytical method for organic compounds that combines gas chromatography (as a separation method) with mass spectrometry (as a detection method).

Half-life

The chemical half-life, or time (usually in years) required for one-half of the initial concentration of a CAH to degrade or chemically transform into other compounds and aqueous species. Biodegradation rate constants and other types of rate constants may be expressed in terms of chemical half-lives. This usage is analogous to the half-life of a radionuclide transforming into a different element.

Historic M2SD

Historic mean plus 2 standard deviations. Each value is calculated from historical analytical data for a specific analyte in a specific well.

**IHSS** 

An Individual Hazardous Substance Site, numbered for identification.

**IMP** 

RFETS Integrated Monitoring Plan, which describes in general terms the components and objectives of the groundwater monitoring program, and how groundwater data will be collected, evaluated and reported. The IMP is updated annually and contains the list of wells in the monitoring program. The IMP also specifies the chemical suites that are analyzed at each well.

**IMPBD** 

The RFETS IMP Background Document, which describes specifics of the groundwater program, and describes the well classes and how groundwater quality data will be collected, interpreted, and reported in compliance with RFCA.

 $K_b$ 

Bulk attenuation rate constant determined for a specific time interval from a plot of natural log of analyte concentration versus distance along a contaminant flowpath. Positive rates indicate that natural attenuation is occurring along the flowpath. The units of  $K_b$  in this report are per year.

 $K_d$ 

The partition coefficient or distribution coefficient in ml/g, is the equilibrium ratio of the mass of a chemical sorbed on a solid phase, to its concentration in aqueous solution. Commonly used as a simple approach to modeling chemical adsorption by soils.

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K<sub>oc</sub> The distribution coefficient in ml/g, describing the adsorption of an organic

chemical from aqueous solution to a substrate of organic carbon in soil. Used

with  $f_{oc}$  to estimate  $K_d$  values for CAHs.

K<sub>p</sub> Point attenuation rate constant determined for a specific location (single

monitoring well) from a plot of natural log of analyte concentration versus elapsed time. Positive rates indicate that natural attenuation is occurring in groundwater near the well. The units of  $K_p$  in this report are per year.

K-H Kaiser-Hill, LLC the contractor engaged by the DOE to close the RFETS.

Lathe Coolant This coolant, as used at RFETS, was a mixture of 70% hydraulic oil and 30%

carbon tetrachloride, probably mixed by volume. Density calculations suggest

that it should behave as a DNAPL.

LCS Laboratory control sample. A type of QC sample that originates in the analytical

laboratory.

LIC Line-item-code (LIC) is assigned by ASD to identify specified analyte suites,

analytical methods, and required detection limits.

ln C Natural log of the concentration of an analytes' concentration. Commonly used

as the vertical axis variable on time series plots that were constructed to provide

attenuation rate information.

LNAPL Light non-aqueous phase liquid. LNAPLs are less dense than water and often

float on top of the groundwater table. Gasoline and jet fuel are examples of

LNAPLs.

MC Methylene chloride, or dic hloromethane, CH<sub>2</sub>Cl<sub>2</sub>, forms from the biodegradation

of CF and is the second daughter of the CT decay chain.

MCL Maximum contaminant level.

Methane Methane, CH<sub>4</sub>, may be produced by the reductive dechlorination of

chloromethane. Methane is the fourth daughter product of the CT decay chain.

Methanol Methyl alcohol, CH<sub>3</sub>OH, is (like methane) potentially the fourth daughter product

of the CT decay chain. Methanol is produced by the hydrolysis of

chloromethane.

mg/L Milligram per liter.

Micromolar A concentration in micromoles (µMoles) of a compound per liter of water.

Mineralized The biodegradation literature uses this term to denote the final breakdown (or

mineralization) of an organic molecule, such as vinyl chloride, into inorganic end

products like carbon dioxide and water.

MNA Monitored natural attenuation, a potential remedial option for groundwater

contaminated with CAH compounds.

MSPTS Mound Site Plume Treatment System

NAPL Non-aqueous phase liquids in the general sense. May be mixtures of chlorinated

solvents, or mixtures of solvents and hydrocarbons of unknown density but likely

occurring as a separate phase.

ORP Oxidation-reduction potential measured on a groundwater sample as a voltage

between an inert platinum electrode and a reference electrode, usually of

Ag/AgCl. It is normally reported in millivolts. See also Eh.

Parent Parent compounds, or primary compounds refer to the nondegraded solvent

compounds that were originally released to soil and groundwater. For example, the parent carbon tetrachloride degrades to daughter compound chloroform.

PCA Perchloroethane, e.g., 1,1,1,2-PCA, a potential parent of 1,1,2-TCA.

PCE Tetrachloroethene, or perchloroethylene, CCl<sub>2</sub>=CCl<sub>2</sub>, was an important solvent

used in industrial operations at RFETS and is the parent molecule of its decay

chain. One solvent brand used at RFETS was called Perclene.

Plume is used in this report to denote a mapable area of groundwater in which the

concentration of a single CAH exceeds its action level or a water quality

standard. A plume may be derived from dissolution of CAHs from a single area of soil contamination, or from multiple source areas. The plumes discussed in this report are usually bounded by concentrations at the Tier II or I groundwater

action level.

Porous Medium A hydrologic term for the soil, unconsolidated sediments, or porous rock through

which groundwater slowly flows. It is also called the aquifer matrix.

PSA Plume signature area, a local area of RFETS defined for modeling purposes

where groundwater contains detectable concentrations of one or more chlorinated

solvents. A PSA "is the result of the signature left behind by a plume or a

number of plumes associated with a single source or a combination of sources in the same vicinity" (K-H, 2003b). Each of more than two dozen PSAs identified

at the RFETS has been assigned an integer identification number.

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Pu The chemical symbol for plutonium is Pu.

QC Quality control, as in a QC sample generated for quality control purposes.

RCRA Resource Conservation and Recovery Act

RD Reductive dechlorination, the most important anaerobic biodegradation process.

REAL REAL is a SWD code identifying primary or real samples, as opposed to QC

samples. In this report, REAL refers to data describing the primary groundwater

sample collected at a well or building drain during a sampling event.

Redox A geochemical term for oxidation-reduction reactions. A characteristic of redox

reactions is that they may be broken into separate oxidation and reduction half-

reactions involving electron transfer.

RFCA Rocky Flats Cleanup Agreement, a legal agreement between CDPHE, U.S. EPA,

and U.S. DOE.

RFETS Rocky Flats Environmental Technology Site

Rinsate A OC sample generated by pouring clean deionized water over or through

sampling equipment that was previously decontaminated. Analysis of rinsate samples (RNS) may indicate cross-contamination due to incomplete or improper

decontamination procedures.

RNS A SWD code identifying data describing a rinsate sample.

Source area A CAH contaminant source area is the geographic location and extent of a CAH

spill, or leaking underground tank, or area of leaking solvent drums that may

dissolve in groundwater migrating through the area.

Steady-State Plume A plume that does not grow or shrink substantially during a specified period of

observation. Chapter 5 of this report considers plumes to be at steady-state when

their predicted and measured plume lengths agree within ±25% during a

measurement period.

Sulfidic A sulfidic redox environment describes groundwater that contains measurable

hydrogen sulfide (H<sub>2</sub>S). The microbially-mediated process of sulfate reduction

often produces sulfidic environments.

SUR A SWD code indicating analytical data for surrogate compounds.



Surrogate Compound Any of a set of distinctive compounds that do not occur in nature and are not

> normally found in environmental samples. Analytical procedures for VOA and SVOA analysis often require one or more surrogates to be spiked into samples prior to their analysis, as a quality control check. SUR data are reported by the

laboratory and may be used in data validation.

**SVOA** Semivolatile organic analyte.

**SWD** The Soil Water Database maintained by Analytical Services Division of Kaiser-

Hill. It is the official environmental database for RFETS.

T Uppercase T or lowercase t is frequently used to denote elapsed time since a

reference date, or since time zero  $(T_0 \text{ or } t_0)$ .

**TCA** Trichloroethanes in general, 1,1,1-trichloroethane (CH<sub>3</sub>-CCl<sub>3</sub>), and 1,1,2-

> trichloroethane (CHCl<sub>2</sub>-CH<sub>2</sub>Cl). 1,1,1-TCA is the more common TCA isomer in groundwater at RFETS and is the parent of a decay series. It decays mainly to 1,1-dichloroethane, or to acetic acid (acetate ion), but a fraction may decay to

1,1-dichloroethene.

**TCE** Trichloroethene, CHCl=CCl<sub>2</sub>, is a manmade industrial solvent that was used at

RFETS and is the parent of its own decay chain. TCE, however, is also the first

daughter product in the dechlorination of PCE. Thus the origin of TCE

concentrations in groundwater is not always certain.

**TDS** Total dissolved solids

TIC Tentatively identified compound

Analyte-specific action level for groundwater at RFETS. It is defined in RFCA. Tier I

Tier I is defined as 100 times the Tier II action level.

Tier II action levels are defined in RFCA. They based on the CDPHE basic Tier II

> standards for groundwater and are generally equivalent to maximum contaminant levels (MCLs). Tier II action levels are intended to protect surface water quality at the RFETS. Tier II values are used as natural attenuation goals in this report.

TOX Total organic halide concentrations in groundwater analyzed by EPA method

> 9020 or a similar method. TOX detects CAHs containing chlorine, bromine or iodine, but not fluorine. TOX analyses are usually reported as µg/L chloride.

**TPH** Total petroleum hydrocarbons

trans-Refers to the trans- isomeric configuration, usually of halogen atoms on opposite sides of a carbon double bond. Microgram per liter. μg/L Micromolar, meaning micromoles per liter of water. μM Micromoles, 10<sup>-6</sup> moles of a compound. A mole contains the Avogadro number μMole of molecules, and may be converted to mass by multiplying by the molecular weight. Vinyl chloride, or chloroethene, CH<sub>2</sub>=CHCl, is produced naturally by VC dechlorination of any of the DCE isomers. VC can be thought of as the third daughter of PCE decay, or the second daughter of TCE decay. VOA Volatile organic analyte. CAHs are volatile organic analytes analyzed from groundwater sampled and shipped in VOA vials. Volatile organic compound, a synonym for VOA. VOC A contaminant plume of VOC compounds dissolved in groundwater. **VOC Plume** Validation and verification of environmental quality data V&V Value on the left is greater than the value to the right of the > symbol. Value on the left is less than the value to the right of the < symbol. < Lambda, the biodegradation rate constant. λ Means similar to, or nearly equal, when used to equate two parameters. Multiplication symbol. One-dimensional, as opposed to 2D or 3D. 1D

### 1 INTRODUCTION

This report presents evidence of the extent of natural attenuation processes reducing the concentrations of CAHs found in groundwater at RFETS. It uses available groundwater quality data to estimate the rates of natural attenuation. The report also uses a number of geochemical lines of evidence to evaluate the occurrence of biodegradation at RFETS.

The report consists of eight (8) sections. Section 1, Introduction, and Section 2, Objectives, introduce the report and the reasons for performing this evaluation. Section 3 Methods, explains the evaluation strategy, reviews natural attenuation processes, and discusses the "lines of evidence" to be used to evaluate the natural attenuation of CAHs detected in groundwater at RFETS. Section 3 discusses the types and sources of water quality data used in this investigation. A general conceptual model is also presented in Section 3. Section 4 briefly describes the hydrogeologic setting of the IA at RFETS and its surroundings. Section 4 also discusses how, when, and where chlorinated solvents were used in industrial processes at the RFETS and potentially released to the environment. Section 5 presents the interpretations of data describing the rates and extent of natural attenuation of CAHs in groundwater at the RFETS. Sections 6 and 7 present the conclusions and references, respectively. Appendices A through I provide supporting calculations and other documentation of the evaluation. The appendicies are included on a compact disk (CD) in the pocket at the back of the report.

The report does not attempt to fully address the requirements of the EPA OSWER Directive on MNA (EPA,1999a). It does not address the potential applicability of MNA as a groundwater remedial option at RFETS. If this report demonstrates that natural attenuation is operating at reasonable rates, then a logical next step may be to evaluate MNA as a groundwater remedial action at RFETS.



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### 2 OBJECTIVES

The main objective of this evaluation is to determine the extent of natural attenuation processes occurring at the RFETS that naturally reduce the concentrations (or mass) of CAHs dissolved in groundwater. This work is intended to provide the following support:

- Provide an assessment of natural attenuation rates to assist DOE in strategic planning for groundwater remediation and Site closure;
- Provide an evaluation to assist the K-H Water Monitoring and Compliance Program (WMCP) in its periodic rescoping of groundwater monitoring requirements at RFETS and in planning for Site closure;
- Support K-H Environmental Restoration (ER) personnel in evaluating and designing accelerated actions for groundwater contaminated with CAHs; and
- Provide biodegradation rate constants to support the on-going CAH contaminant transport modeling.

This evaluation also examines the spatial distribution and concentrations of CAHs through time in Site groundwater. The investigation is based on historical groundwater analytical data collected between 1986 and August 2003 to satisfy a wide variety of data quality objectives (DQOs). Many of these DQOs pertained to data collection for characterization of CERCLA Operable Units during the early 1990's, or for detection and monitoring of a wide variety of potential contaminants in Site groundwater. Only a small percentage of these groundwater analytical data was originally collected for the purpose of evaluating natural attenuation.



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# 3 EVALUATION SCOPE, STRATEGY, AND METHODS

This section discusses the scope, strategy, and methods used to develop the CAH natural attenuation evaluation. The evaluation is based on the applicable groundwater analytical data retrieved from the Soil and Water Database (SWD). SWD is the official repository of environmental data for the RFETS. Post-processing of the retrieved data is also discussed in this section.

# 3.1 Evaluation of Natural Attenuation - Scope and Strategy

This evaluation considered the natural attenuation of CAHs and their degradation products on a Site-wide basis and in selected contaminated areas of interest, termed plume signature area (PSAs), defined by K-H (2003b). A PSA is defined as "the result of the signature left behind by a plume or a number of plumes associated with a single source or a combination of sources in the same vicinity." The occurrence and quantification of natural attenuation was demonstrated using various lines of evidence presented in the literature and calculations using Site-specific groundwater quality data.

# 3.1.1 Analytes of Interest

The most widespread and geochemically significant CAHs found in groundwater at the RFETS were evaluated. These constituents include CAHs that were widely used as industrial solvents, degreasers, and cleaning agents. Additional CAHs have been analyzed, but not detected in Site groundwater, and thus, are not discussed further. Analytical data for these additional CAHs are presented in Appendix H.

CAHs are defined in this report as chlorinated derivatives of the saturated alkane and unsaturated alkene families of hydrocarbon compounds (Hart and Schuetz, 1966). Technically, CAHs may include the alkyne family and chlorinated cyclic compounds like cyclopentyl chloride (Rittmann et al., 1992). However, the CAH compounds of interest in this evaluation include chlorinated, one to four carbon, straight-chain alkanes and alkenes. Note that CAHs specifically exclude aromatic hydrocarbons with one or more benzene rings, like chlorobenzene and polychlorinated biphenyls (PCBs). This report does not consider halogenated hydrocarbons containing fluorine, bromine, or iodine.

Common CAHs used at the Site include carbon tetrachloride (CT), tetrachloroethene (PCE), trichloroethene (TCE), and 1,1,1-trichloroethane (TCA). This evaluation is concerned with the degradation of these parent solvents into molecularly lighter degradation products, called daughter products. The daughters are also CAHs. Common daughter CAHs include dichloroethene isomers (DCE), vinyl chloride (VC), chloroform (CF), and methylene chloride (MC). CAH daughter products eventually degrade into simple organic molecules (e.g., metabolic byproducts like ethane and methane) and inorganic substances, such as chloride and bicarbonate. A host of other organic and inorganic analytes and field parameters were also examined to understand the geochemical environment and



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degradation of the CAHs. Of particular interest are analytes that may indicate groundwater redox conditions, such as dissolved oxygen (DO), oxidation-reduction potential (ORP), nitrate, sulfate, sulfide, ferrous iron, and total dissolved iron.

Indicators of fuel spills (e.g., benzene, ethylbenzene, xylenes, toluene, and total petroleum hydrocarbons (TPH)) are also of interest since they may assist in the biodegradation of CAHs. Other potential contaminants at the RFETS, such as radionuclides, PCBs, pesticides, herbicides, most semivolatile organic compounds, and most metals are not relevant and were not considered in this evaluation.

Groundwater quality data for the above-mentioned analytes of interest were available from 705 monitoring wells and drains located within the IA and adjacent areas. Figure 3-1 shows the area evaluated and the locations of the 705 wells. A CAH plume in the PU&D Yard (north of the IA) was not considered because it is undergoing enhanced bioremediation. The Present Sanitary Landfill was also not evaluated because it lacks a well-defined external CAH plume.

### 3.1.2 Areas of Interest

Dissolved CAHs have been measured in groundwater at more than two dozen PSAs. Most PSAs lie within the IA or on adjacent property, such as the East Trenches area. K-H (2003b) performed initial screening of the PSAs and ranked them by their importance to on-going fate and transport modeling. This report evaluates natural attenuation on a site-wide basis and then examines the 7 most important PSAs (numbered 2, 3, 5, 7, 10, 12, and 14) identified by K-H (2003b). The original PSA numeric designations are used throughout this report, although subsequent revision of the VOC Transport Modeling Report (K-H, 2003b) may have re-numbered the PSAs.

The rectangular outlines of these seven PSAs evaluated are shown on Figures 3-1 and 3-2. The main purpose of Figure 3-2 is to identify selected groundwater flowpaths labeled A, B, or C in each PSA that were used to evaluate the groundwater quality data and provide interpretations as to whether natural attenuation is occurring at the site. These flowpaths are approximate and vary somewhat with annual and seasonal changes in the water table.

# 3.1.3 Lines of Evidence Demonstrating Natural Attenuation

This section explains lines of evidence for quantifying the extent of natural attenuation, and specifically of biodegradation at RFETS, as they provide the framework for the data interpretations in Section 5.



Lines of evidence used to evaluate the natural attenuation of organic compounds in groundwater include the following (Wiedemeier et al., 1995, 1997, and 1999):

- Historic trends in contaminant concentration data may show plume stabilization over time. The
  plume should not be growing in extent and primary contaminants should not be increasing in
  concentration;
- Plume stabilization may be evaluated by making isopleth maps (discussed below) of historic contaminant concentrations in groundwater. Maps representing different time periods may be visually compared. Alternatively, statistical methods (e.g., the Mann-Whitney U test, also called Wilcoxon rank-sum test) have been used in published literature to demonstrate plume stabilization at some non-RFETS sites. Experience has shown that visual evidence (maps and graphs) is more readily accepted by stakeholders than the numeric results of a statistical method;
- Analytical data may be used to demonstrate that the geochemical environment is suitable for biodegradation to take place and/or that biodegradation has occurred. Suitable evidence includes various two and three-dimensional charts and maps of the data that demonstrate:
  - Decreasing downgradient concentrations of parent compounds, for example CT or PCE;
  - Increasing downgradient concentrations of daughter compounds, for example chloroform and methylene chloride (CT daughters);
  - Increasing downgradient concentrations of metabolic by-products, for example, chloride ion;
  - Local depletion (relative to unimpacted groundwater) of electron acceptors (oxidants). Example oxidants include dissolved oxygen (DO), nitrate, Fe(III), Mn(IV), sulfate, PCE, and TCE; and
  - Local accumulation of electron donors (reductants). Example reductants include sulfide ion, Fe(II), and Mn(II).
- The overall impact of natural attenuation processes at a given site can be assessed by evaluating the rate that contaminant concentrations are decreasing either spatially or temporally (Newell et al., 2002). Analytical data for parent CAHs and their daughter products may be used to estimate several types of first-order attenuation rate constants. Use of site-specific rate constants for evaluating natural attenuation has been endorsed by guidelines issued by EPA (1999a) and the American Society for Testing and Materials (ASTM, 1998). Derivation and use of these constants in evaluating natural attenuation is discussed later in this section;



- If sufficient well control and groundwater analytical data exist, it may be feasible to demonstrate a loss of contaminant mass over time;
- Analytical or numerical solute transport models may be used to test the relative influences of the
  attenuation processes (e.g., sorption, dispersion, biodegradation, dilution, etc.) on the transport of
  the parent and daughter contaminants in migrating groundwater. A well-calibrated model may
  be able to reproduce the approximate extent, shape, and chemistry of an existing plume from
  historical contaminant source area information; and
- Microcosm investigations may demonstrate that the porous medium and groundwater at a site contains suitable bacteria for biodegradation of the contaminants and can support biodegradation at a reasonable rate. Wiedemeier et al. (1999) stated that "microcosm studies should only be undertaken when they are absolutely necessary to obtain biodegradation rate estimates that could not be obtained using the other lines of evidence or when the specific mechanism of degradation is not known." Microcosm studies have not been performed on environmental media at RFETS.

The following sections discuss in detail the specific lines of evidence that are applied in this evaluation.

# 3.1.3.1 Wiedemeier Biodegradation Screening System

A ranking system, referred to as Wiedemeier scores, has been developed as a screening tool to quickly assess subsurface biodegradation potential (Wiedemeier et al., 1997; EPA, 1998). This system is based on the following generally accepted concepts:

- Specific geochemical environments are required for biodegradation to occur at an appreciable rate; and
- Biodegradation reactions cause predictable changes in groundwater chemistry (EPA, 1998).

If most of the needed analytical parameters have been measured, then their concentrations may be compared and assigned points according to criteria found in Table 3-1. Minor differences in scoring exist between the two documents that describe this system (Wiedemeier et al. 1997; EPA (1998)). Table 3-1 indicates how scoring was performed for the present investigation. Criteria presented in Table 3-1 are based on Wiedemeier et al. (1997) and EPA (1998).

Note that point scores based on Table 3-1 may be biased low because RFETS lacks analytical data for the following parameters, which are typically included in a Wiedemeier score:



Table 3-1 Wiedemeier System for Screening Biodegradation Potential

Analyte	Concentration	Interpretation	Points Awarded	
Dissolved Oxygen	<0.5 mg/L	Dissolved oxygen is tolerated below 0.5 mg/L. Higher concentrations suppress reductive dechlorination.	3	
Dissolved Oxygen	>1.0 mg/L	Vinyl chloride can be aerobically oxid ized, but reductive dechlorination is suppressed.	-3	
Nitrate and/or Nitrate/Nitrite	<1 mg/L	At higher concentrations nitrate competes with the CAH reductive pathway.	2	
Ferrous Iron (Fe <sup>2+</sup> )	>1 mg/L	Indicates a reductive pathway is possible	3	
Sulfate	<20 mg/L	At high concentrations it may compete with the CAH reductive pathway.	2	
Sulfide	>1 mg/L	Indicates a reductive pathway is possible	3	
Methane	>1 mg/L	Vinyl chloride may accumulate	3	
Methane	>0.1 and <1	Methane is produced by methanogenesis and is a daughter product of the complete reductive dechlorination of carbon tetrachloride.	2	
Oxidation Reduction Potential (ORP)	<50 mV (Ag/AgCl)	Indicates a reductive pathway is possible	1	
Oxidation Reduction Potential (ORP)	<-100 mV	Indicates a reductive pathway is possible	2	
Field-Measured pH	<5 or >9	Outside tolerated pH range	-2	
DOC or TOC	>20 mg/L	Carbon and energy source supporting dechlorination	2	
Groundwater Temperature	>20°C	Reaction rates are accelerated above 20°C	1	
Total Alkalinity (as CaCO <sub>3</sub> )	>2 times background	Reductive dechlorination results in increased alkalinity.	1	
Chloride	>2 times background	Chloride ion is a product of the dechlorination of CAHs.	2	
втех	>0.1 mg/L	Benzene, toluene, xylenes and ethylbenzene from gasoline spills are a carbon and energy source for bacteria.	2	
richloroethene Detected		Although TCE was used at RFETS, it is assumed (for scoring purposes) that the detected TCE is a daughter of PCE. If it was manmade TCE it would get no points.	2	
DCE (cis - or trans-)	Detected	Assumed to be daughters of TCE	2	
Vinyl Chloride	Detected	DCE daughter product	2	
Ethene or Ethane	>0.1 mg/L	Daughters of vinyl chloride	3	
Ethene or Ethane	>0.01 mg/L and <0.1	Daughters of vinyl chloride	2	
Chloroethane	Detected	Daughter of 1,1-DCA, or vinyl chloride under reducing conditions	2	



- Dissolved hydrogen gas (assigned 3 points if >1 nanomolar);
- Volatile fatty acids (2 points if >0.1 mg/L); and
- Dissolved carbon dioxide (1 point if >2 times background).

Wiedemeier scores were developed for the Site using Access queries to compare the individual constituent concentrations and assign points. Data were grouped across all sampling dates for each parameter at each well to maximize the available parameters. Minimum, mean, and maximum point values were then summed from the parameter data for each well. Missing analytical data usually lower the overall score for a well, although missing negative point values could raise the overall score.

The overall Wiedemeier scores are interpreted at follows (Wiedemeier et al., 1997):

•	Negative to 0 points	No evidence;
•	1 to 5 points	Inadequate evidence of biodegradation of CAHs;
•	6 to 14	Limited evidence of biodegradation;
•	15 to 20	Adequate evidence of biodegradation; and
•	>20	Strong evidence of biodegradation.

Wiedemeier scores were computed for groundwater quality data at RFETS and are discussed in Section 5.1.1.

### 3.1.3.2 Rate Constant Review

Several types of first-order rate constants (K) were computed and discussed in this evaluation. K is used in the first-order chemical decay equation,  $C = C_o e^{-KT}$ , to compute contaminant concentrations (C in  $\mu g/L$ ) at elapsed time T (years). The initial CAH concentration (in  $\mu g/L$ ) is  $C_o$ . K has units of reciprocal time (T<sup>-1</sup> or per year). Therefore, the exponent KT is unitless and C has the same concentration units as  $C_o$ . Positive values of K indicate contaminant attenuation via first-order chemical decay. It may be helpful to express the rate constant in terms of a chemical half-life. For example, a half-life of 10 years means that the concentration of the chemical should decay to half its initial concentration after 10 years. The rate constant for this decay can be expressed as a half-life (in years) via the equation, half-life = 0.6931/K. Note that half-lives and K values are inversely related. Therefore, low K values indicate long half-lives, while high K values mean short half-lives.



Figure 3-3 illustrates the above concepts by showing several examples of first-order decay curves. These curves show various rates that an initial contaminant concentration of  $1,000 \mu g/L$  will decrease (attenuate) through time. Each curve is constructed for a different assumed half-life (i.e., decay constant). Note the inverse relationship between K and half-life. The curve drawn at a 100-year half-life has a low K of 0.007 per year, while the 2-year half-life curve has a large K of 0.347 per year.

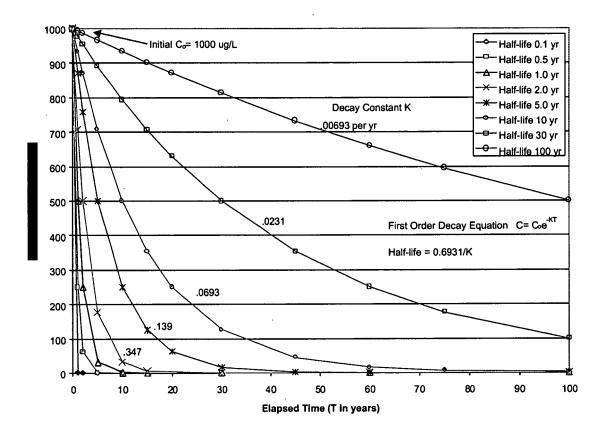


Figure 3-3 Example First-Order Decay Curves

The following sections discuss specific applications of first-order rate constants to the present investigation of natural attenuation and the biodegradation of CAHs. Additional background regarding rate constants and coupled parent-daughter decay is provided in Appendix I which compares chemical and radioactive decay processes.

#### 3.1.3.3 Point Attenuation Rate Constants and In C Versus Time Plots

One means of evaluating the efficacy of natural attenuation is to estimate the rates of attenuation processes and then use these rates to predict the time required to achieve remediation objectives. The rates of natural attenuation, and particularly of biodegradation, are of great interest to regulators and other

stakeholders. This is particularly true if monitored natural attenuation is proposed as a remedial alternative for groundwater clean-up.

Charts may be constructed that show how ln C of an analyte has changed in groundwater during an extended time period (T) for a single well (or "point"). Because changes through time are of interest and natural attenuation of CAHs occurs slowly, many years of monitoring data are desirable. Concentration data used to construct these charts are obtained from periodic sampling and analysis of groundwater at wells within a CAH plume.

This report refers to these charts as ln C-vs-T plots. They are a specialized type of time-series plot. CAH concentrations often plot along a straight line on ln C-vs-T plots. The slope of this line can be related to a first-order decay process. Biodegradation typically obeys a first-order rate law which means that decay rates are proportional to the log of the available contaminant concentration (Brady et al., 1999).

Constants derived from  $\ln C$ -vs-T plots are called  $K_p$  or point attenuation rate constants. The value and use of these rate constants is discussed below:

- Point attenuation rate constants indicate how a contaminant concentration changes with time at an
  individual well. Positive constants indicate decreasing concentrations through time, while
  negative constants indicate increasing contaminant concentrations over time;
- K<sub>p</sub> mainly reflects the change in source strength over time, but also includes effects from other natural attenuation processes operating at and upgradient of the point of measurement (Newell et al., 2002). In other words, biodegradation is not distinguished from other natural attenuation processes such as sorption, dispersion, or volatilization. Therefore, K<sub>p</sub> rates are a lumped parameter that does not solely represent the rate of biodegradation;
- K<sub>p</sub> represents the persistence in source strength over time at wells located within the source zone. It can be used to estimate the time required to achieve a remediation goal or action level at these source wells (Newell et al., 2002); and
- Given sufficient time and a finite source, the concentration profiles of CAH plumes in groundwater should eventually retreat back towards the source as it slowly decays. In this case, the life-cycle of the plume is controlled by the attenuation rate of the source and can be predicted from ln C-vs-T plots of data from the most contaminated wells (Newell et al., 2002).

Wells selected to calculate  $K_p$  rates are usually located along or near the axis of a contaminant flowpath. Wells in the source area with the highest contaminant concentrations may be used to estimate plume longevity as discussed above. Older wells have a longer history of water quality monitoring and tend to



show more reliable trends in water quality. Because more than a single concentration value may exist for an analyte in a well during a single sampling event these data may be averaged.

This report contains numerous ln C-vs-T plots showing the natural log of analyte concentration (ln C) on the vertical or y-axis and elapsed time (T) in days on the x-axis. Elapsed days are computed by examining the date range of the available data and subtracting the date of the oldest groundwater sampling event (i.e., the reference date) from each of the more recent sampling events. This yields elapsed days since the well was first sampled.

If a ln C-vs-T plot shows a linear trend and contains at least three data points, then a linear regression may be fitted to the data. According to Newell et al. (2002), the negative slope of this regression line is a first-order attenuation rate constant  $(K_p)$  with units of inverse time (i.e., day or per day). If contaminant concentrations are decreasing through time, then the slope of the regression line is negative and  $K_p$  is positive. If the well is located within the source area, then  $K_p$  provides an estimate of the contaminant source strength over time and it can be used to estimate the time required to reach a remediation goal  $(C_g)$  at that location (Newell et al., 2002). The time required to reach the remediation goal can be calculated using  $T = -\ln(C_g/C_i)/K_p$ , where  $C_i$  is the starting or initial concentration.

Because  $K_p$  represents a first-order decay process, the decay can also be described in terms of a half-life, where half-life is equated to  $0.6931/K_p$ . If  $K_p$  has units of per year, then the equivalent half-life has units of years. Per day units may also be used.

Numerous In C-vs-T plots were constructed for contaminants within the RFETS PSAs. These plots and their estimated rate constants are discussed in detail in Section 5.

#### 3.1.3.4 Bulk Attenuation Rate Constants and In C Versus Distance Plots

The ln C of CAH concentrations may also be plotted versus its migration distance (D) along a contaminant flowpath from a source area. These plots are termed ln C-vs-D charts. Ln C-vs-D plots have the useful property that ln C data often plot along a straight line. The slope of a fitted regression line can be used to estimate a bulk attenuation rate constant (K<sub>b</sub>) and this slope can be used to calculate biodegradation rates. The bulk attenuation rate constant has the following properties and uses:

K<sub>b</sub> rate constants represent the overall attenuation rate attributed to all natural attenuation
processes operating along the flowpath during a specific time interval. As with K<sub>p</sub> rates, K<sub>b</sub> rate
constants also do not distinguish biodegradation from other natural attenuation processes such as
sorption, volatilization, dispersion, or dilution;



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- K<sub>b</sub> rate constants are most useful for predicting how far a plume will migrate before a remediation goal is met. In general, this calculation is performed for specific contaminants of concern (COCs) using data for a specific period. If the mapped plume (or estimated plume length during the period) already extends beyond its predicted extent, then the plume is expected to shrink back towards its source in the future. If the mapped plume is shorter than the predicted extent, then it is expected to continue to migrate (i.e., expand) downgradient. Because of the uncertainty in a K<sub>b</sub> estimate, this report considers plumes to be at steady-state (i.e., neither shrinking or expanding) if their predicted and measured plume lengths agree within ±25%;
- Because K<sub>b</sub> constants can be developed for specific time periods, the extent of the plume can be
  predicted and compared with the mapped plume extents for the appropriate period. RFETS has
  about 18 years of analytical data for some COCs. Where possible, K<sub>b</sub> rate calculations were made
  for two-year periods to empirically test the accuracy of some predicted plume extents based on
  the calculated K<sub>b</sub> values;
- K<sub>b</sub> rate constants can also predict the elapsed time required to meet an attenuation goal.
   However, K<sub>p</sub> constants are generally considered superior to K<sub>b</sub> constants for this purpose; and
- Because a source will continue to replenish dissolved COCs, K<sub>b</sub> rates should not be used to
  estimate how long the plume will persist unless the source has been completely removed (Newell
  et al., 2002).

Ln C-vs-D plots were prepared to determine bulk attenuation rate constants for individual CAHs in each of the PSAs of interest during periods with sufficient data. These plots were made by first sketching a flowpath on the map of the PSA (Figure 3-2) and projecting nearby wells onto the path (using lines drawn perpendicular to the path and through each well). A starting zero point was assumed at a well in or just upgradient of the presumed source area. Distances were measured on the map from the zero point, downgradient to where each well projected onto the path. These horizontal map distances were converted into feet and the distance to each well on the path was tabulated in an Access table. The table was sorted first by PSA, then by flowpath (1 to 3 paths were defined), and finally by increasing distance along the flowpath. This table was used in queries to create datasets to construct ln C-vs-D plots.

Analytical data for ln C-vs-D plots were split into two-year time intervals. These intervals were used to maximize data availability, average or cancel potential seasonal variations in concentration data, and to average sampling and analytical variability. Data collected during the time period were averaged at each well for the analyte of interest. The ln C-vs-D plot was then constructed by plotting the natural log of the mean concentration at each well along the flowpath versus the distance of each well down the path.

A spreadsheet program was used to fit a linear regression line to the ln C-vs-D data for each analyte. When this line is a good fit to the data and has a negative slope, it indicates that the chemical



concentration is decreasing (per a first-order decay process) as it migrates along the flowpath. This slope is used, together with other parameters, to estimate  $K_b$  (Newell et al., 2002).

The ln C-vs-D plots were used to determine  $K_b$  for individual CAHs in each of the PSAs of interest at various time intervals. The time interval of each plot was fixed at two calendar years to evaluate potential plume concentration changes through time. The date range of the groundwater quality data at RFETS extends from 1986 to 2003, a period of approximately 18 years. Time intervals were defined to start on January 1<sup>st</sup> of even numbered years and terminate on December 31<sup>st</sup> of the following odd numbered year. This divided the data into a maximum of 9 historical time intervals or periods.

These charts were produced by plotting only detected CAH concentrations because nondetected data are of little value in generating attenuation rate constants. If three or more data points (i.e., mean CAH concentrations at 3 or more wells along the flowpath) were available for the time period and were reasonably linear on the plot, then a regression line was fitted. The least squares regression line was fitted using a spreadsheet program.

K<sub>b</sub> rate were computed by multiplying the negative of the slope of the regression line times the contaminant velocity (Newell et al., 2002). The contaminant velocity (V<sub>c</sub>) equals the groundwater velocity (V<sub>w</sub>) divided by the retardation factor (R). UHSU groundwater velocities representative of each PSA were obtained from the Final 2002 RFCA Annual Groundwater Monitoring Report (K-H, 2004).

The retardation factor (R) is calculated using  $R = (\rho * K_d / n_e) + 1$ , where  $K_d$  is the partition or distribution coefficient ( $K_d$ ),  $\rho$  is the soil bulk density, and  $n_e$  is the effective porosity (EPA, 1999b). The average bulk density of UHSU borehole materials is 2.1 g/mL based on analyses reported in the RFETS Hydrogeologic Characterization Report (EG&G, 1995). The effective porosity of the UHSU was assumed to be 0.1, which agrees with its usage in the 2001 and 2002 RFCA Annual Groundwater Monitoring Reports.

 $K_d$  was estimated using  $K_d = K_{oc} * f_{oc}$ , where  $K_{oc}$  is the distribution coefficient for sorption by the organic carbon in soil and  $f_{oc}$  is the fraction of organic carbon in the soil-(Langmuir, 1997).  $K_{oc}$ -values for individual CAHs were selected from a compilation by EPA (1998, Table B.2.1). To be conservative and minimize solute retardation, the smallest  $K_{oc}$  was selected when more than a single published value was available. An average  $f_{oc}$  for the UHSU was calculated from 347 measurements of total organic carbon (TOC) representing 123 boreholes at RFETS. The average  $f_{oc}$  value used in this evaluation was 0.00144.

Once K<sub>b</sub> rates are calculated, they are most useful for predicting the future extent or downgradient boundary of a plume (Newell et al., 2002). For this purpose, a contaminant plume is defined as the region in which concentrations of the CAH dissolved in groundwater equal or exceed the groundwater action level. Because RFCA established Tier II groundwater action levels for protection of surface water at RFETS, this report uses the Tier II groundwater action level for each CAH as the goal for natural



attenuation (CDPHE, DOE, EPA,1996, 2003; K-H, 2000). Appendix G presents Site-specific groundwater action levels and their use in this report.

The maximum concentration of each CAH on the ln C-vs-D plot is assumed to be spatially associated with a primary NAPL source area or it represents a secondary daughter product generated by biodegradation. If the upgradient maximum concentration is less than the Tier II action level for the compound, then the plume is considered to have zero length. In other words, CAH concentrations less than Tier II do not constitute a contaminant plume in Site groundwater. In this report, the measured plume length existing during the period of interest is conveniently defined as the flowpath length between the upgradient maximum concentration and the path distance to the farthest downgradient Tier II concentration boundary. If the Tier II boundary falls between two downgradient wells with detected CAH concentrations, the boundary distance is interpolated from inspection of the dataset. If the Tier II boundary lies beyond the well with the last detected concentration (greater than Tier II), then an estimate is made of the additional path distance required for attenuation to the Tier II level.

Note that the above plume length definition shortens plumes by a small percentage because it ignores the segment of plume length between the upgradient Tier II boundary and the well with the maximum concentration. However, the definition used in this report is convenient for comparing the measured plume length against the predicted or future plume length.

The travel time (T) required for the maximum concentration ( $C_m$ ) to decay to the attenuation goal ( $C_g$ ) is given by  $T = -ln(C_g/C_m)/K_b$  (Newell et al., 1998). The predicted length (L) of the plume in the future is then predicted using  $L = T^*V_c$ . L represents the predicted attenuation distance from the well of maximum CAH concentration to the farthest downgradient Tier II boundary. Note that these path lengths are theoretical projections that assume that  $K_b$  remains constant through time, and that no physical barrier or groundwater discharge area intersects the plume prior to its reaching the full Tier II attenuation distance.

K<sub>b</sub> values calculated for the Site are discussed in Section 5. These constants were used to estimate plume behavior in the future to predict if the contaminant plumes will grow, shrink, or remain stable (at steady-state).

# 3.1.3.5 Estimating Biodegradation Rate Constants

Biodegradation is only one of the chemical, physical, and biological processes operative in the natural attenuation of an organic contaminant. However, regulators favor processes which destroy contaminants, and biodegradation is the most important destructive process in the subsurface (EPA, 1998). Therefore, it is important to know how fast biodegradation may be operating at RFETS.

The biodegradation rate constant ( $\lambda$  or lambda) may be used as an input parameter in solute transport modeling. This constant is a model parameter used to estimate the effect of biodegradation on



contaminant migration relative to other attenuation mechanisms. Alternatively,  $\lambda$  may be an output parameter generated by a calibrated solute transport model.

The effects of advection, dispersion, sorption, volatilization, and dilution must be distinguished to attribute observed decreases in contaminant concentration to biodegradation. Biodegradation rate constants have been estimated by a variety of methods discussed in the published literature. This evaluation uses the well known method proposed by Buscheck and Alcantar (1995). Their method requires that the CAH plume has reached a dynamic steady-state condition. That is, contaminants are being attenuated downgradient at the same rate that they are produced from the source area. This implies that the plume is not rapidly growing or shrinking in size.

The method of Buscheck and Alcantar (1995) is a one-dimensional (1D) analytical solution of the advection-dispersion equation of Bear (1979). This solution is shown below:

$$\lambda = \left(\frac{V_c}{4A}\right) * \left[ (1 + 2AB)^2 - 1 \right]$$

In the above equation,  $\lambda$  is a first-order biodegradation rate constant. Positive values of lambda indicate that biodegradation is taking place. Parameter B is the negative of the slope of the regression line fitted to a ln C-vs-D plot discussed earlier. This sign reversal is not discussed in the original paper, but is mentioned in a related paper by Zhang and Heathcote (2003). The writer has also verified that the sign reversal is necessary in order to duplicate the published results of Buscheck and Alcantar (1995).

 $V_c$  is the retarded velocity of the contaminant in the longitudinal direction along the flowpath. Parameter A is the longitudinal dispersivity in feet. Fetter (1988) states that the value of A can be estimated as one tenth of the plume path length. If the units of  $V_c$  are feet per year, then the units of  $\lambda$  are per year.

EPA (1998) observed that there is a general bias in the literature against publishing negative results and that in many plumes TCE degradation may not have been detected. This reports documents all measured rates whether positive, zero, or negative.

Two-dimensional (2D) and three-dimensional (3D) extensions of the above 1D method were recently published by Zhang and Heathcote (2003). They showed that the method of Buscheck and Alcantar (1995) overestimates the biodegradation rate because it does not consider lateral dispersion or finite source size. In a test case, they found that the 1D method overestimated the rate by 21% and 65% relative to the 2D and 3D solutions, respectively. The impediment to applying the Zhang and Heathcote (2003) method is that it requires knowledge of the x, y, and z dimensions of the CAH source area and estimates of both longitudinal and transverse dispersivities.



There are numerous suspected sources for the VOC plumes observed at RFETS and the dimensions of these sources are generally unknown, as are the field-scale plume dispersivities. Consequently, this evaluation uses the simpler 1D method and recognizes that it likely overestimates the RFETS biodegradation rates.

### 3.1.3.6 Isopleth Maps

Isopleth maps are extremely useful tools for visualizing changes in plume extent and concentration through time and for interpreting a wide variety of biodegradation data. Isopleth maps may be constructed to portray the spatial distribution of analyte concentrations during a specified time interval. A set of such maps may be constructed for the parent contaminants during different periods to determine if the plume extent is growing, stable, or retreating. If the plume is growing in extent, then DOE assumes that an active source is continuing to feed the plume and that active remediation of this source is expected (DOE, 1999a). Similarly, if the concentrations of the parent contaminant appear to be increasing through time at downgradient wells, then this report assumes that an active source continues to introduce dissolved contaminants.

Isopleth maps may be used to show localized depletion of oxidants, reductants, or increasing concentrations of metabolic byproducts associated with a contaminant plume. Isopleth maps of daughter products may also be constructed for different time periods to show that daughter product concentrations are temporally changing as biodegradation occurs. Daughter concentrations may be observed to increase as parent concentrations are decrease. However, daughter concentrations should peak and eventually decrease downgradient.

Depending on data availability, an isopleth map should be constructed for several time intervals to see potential changes in plume extent and concentration. Availability of historic data used in this report led to the use of two-year intervals. Recent conditions have been evaluated by combining year 2002 data with data available up to September 2003. Access queries were used to average the concentrations of the analyte in groundwater at each well within the PSA during the two-year time period. Averaging data over two years has the advantage of removing potential seasonal variations in contaminant concentrations and reducing the combined effects of sampling and analytical variability.

Because of the large volume of analytical data available for the RFETS, it was not practical to hand contour the numerous isopleth maps needed to interpret natural attenuation. Commercial software contouring packages (e.g., Surfer<sup>©</sup> Golden Software) offer a variety of data interpolation routines for gridding the data prior to contouring. Surfer and ArcView<sup>©</sup> (ESRI) software were tested on RFETS data using kriging, natural neighbor, and in verse distance weighting interpolation.

Machine contouring ignores the effects of obstacles such as building foundations, preferential flow directions, or stream drainages and tends to extrapolate contours across them. Another pitfall of both



human and machine contouring is projecting contours unreasonably beyond the nearest well control points. However, the major weakness of the above-mentioned software for natural attenuation work is that it does not easily recognize nondetected contaminant concentrations.

CAH plumes are composed of manmade chemicals that exist only in local areas of groundwater near leaking solvent tanks, leaking drums, burial trenches, or spill sites. Laboratory analyses of groundwater samples collected beyond these local plumes show nondetected CAH concentrations which define the plume boundaries. At RFETS, nondetected values are often more abundant than detected CAH concentrations. Commercial software tends to ignore nondetected values entirely or uses them at face value (e.g., 100U (a nondetected value) is treated as 100 µg/L (a detected value)). This results in contour maps that overestimate the areal extent of plumes by extrapolating them across areas where the chemicals were actually not detected in groundwater. Note that this problem is much less serious for naturally occurring chemicals like chloride, or sulfate which commonly occur over the areal extent of a groundwater body.

To overcome the limitations of most of the commercial contouring software packages, a contouring program, Contours\_Plus <sup>©</sup> (Dirkworks Software), was used to generate isopleth maps. Contours\_Plus uses a standard inverse distance interpolation algorithm for gridding irregularly-spaced map data. This program was selected for use during this evaluation because it was designed to minimize some of the weaknesses of machine contouring of analytical data. Given suitable input datafiles, Contours\_Plus distinguishes detected and nondetected concentrations and limits the extension of concentration isopleths across nondetected regions of the map. The user can also set a maximum radius of influence where contours will not be projected beyond the existing well control. This software also facilitates rapid data assessment because it can directly read Access database tables and can generate dozens of isopleth plots at a time when run in batch mode.

Whether produced by hand contouring or by machine, isopleth maps are data interpretations based on limited control points; thus, the appearance of the resulting maps will depend on the methods, assumptions, and professional judgment of the user. Experimentation with various interpolation and plotting parameters led to the judgment that chemical data for groundwater at RFETS were usually best visualized by log scaling the contour intervals. Log scaling is appropriate because the concentration ranges of analytes, like CT, often span many orders of magnitude from not detected (typically <1  $\mu$ g/L) to hundreds of thousands of  $\mu$ g/L. Comparison of maps produced by interpolation at various powers indicated that fifth order inverse distance gridding yielded maps that emphasized the influence of local data points at low concentrations while minimizing the distant influence of extremely large contaminant concentrations typical of CAH source areas.

Ubiquitous, naturally-occurring analytes like chloride and sulfate have measurable concentrations in almost all wells. Therefore, the concentrations of ubiquitous analytes were sometimes extrapolated over the entire map area. In contrast, manmade chemicals that do not occur everywhere were interpolated



within areas defined by measured concentrations; however, were not projected across areas of well control where the concentrations were not detected. The underlying assumption is that CAHs are not present in groundwater with nondetected concentrations, regardless of the reporting limit. The midpoint distance between a well with detected and another well with nondetected concentrations was used as the inferred boundary of the plume.

Extrapolating data at map edges and into areas far from well control is always perilous. The present investigation tried to control this problem for CAHs by limiting the data extrapolation distance to a maximum of 300 feet from the nearest measured data point.

#### 3.1.3.7 Other Lines of Evidence

The ratios of the cis- and trans- stereoisomers of 1,2-dichlorethene (1,2-DCE) have been used in published literature as an indicator of biodegradation. Manmade 1,2-DCE is a mixture of cis- and trans-1,2-DCE. Biological processes (i.e., biodegradation) mainly produce cis-1,2-DCE (EPA, 1998). Low concentrations of trans-1,2-DCE and 1,1-DCE are also produced by biodegradation (Bouwer, 1994). However, the cis/trans ratio is typically greater than 25 to 1 in groundwater where biodegradation is actively occurring. Therefore, the presence of high cis/trans DCE ratios are considered primary evidence of biodegradation at a site.

The presence of dissolved oxygen (DO) is helpful in the biodegradation of fuel hydrocarbons in groundwater (Wiedemeier, et al., 1995). However, the opposite is true for the biodegradation of most CAHs in groundwater (EPA, 1998); therefore, the presence of DO may limit reductive dechlorination of CAHs. However, a few lightly-chlorinated CAHs, like VC, can be oxidized and destroyed by DO.

### 3.1.4 Relevant Literature

Literature searches were performed to identify relevant books and technical papers concerning biodegradation of CAHs, natural attenuation, and MNA. RFETS-specific environmental reports and papers were also compiled. The most relevant documents were copied and read. The objectives of the literature review were as follows:

- Understand current scientific thinking about natural attenuation processes in general, and biodegradation of CAH in particular;
- Recognize and use accepted lines of evidence to document the occurrence and extent of natural attenuation at the RFETS:
- Summarize information learned from prior evaluations of natural attenuation at the RFETS; and



 Obtain geochemical data for CAHs such as partition coefficients and published biodegradation rates.

RFETS-specific data are presented in the Site-wide and individual PSA discussions of Section 4.

A number of previous investigations have been conducted to characterize CAH-contaminated groundwater in local areas of the Site remedial decisions could be made and systems designed. Most of this work was performed by K-H Environmental Restoration (ER) or by the K-H Water Monitoring and Compliance Program (WMCP). Examples of these investigations include the following plans and reports:

- Industrial Area Sampling and Analysis Plan (DOE, 2001). This document is known as the IASAP and numerous addenda have been written to target specific IHSS groups;
- Sampling and Analysis Plan for Groundwater Monitoring of the Industrial Area Plume (RMRS, 2001);
- Final Proposed Action Memorandum for the East Trenches Plume (RMRS, 1999a);
- Field Implementation Plan for the Mound Site Plume Project (RMRS, 1998a);
- Final Sampling and Analysis Plan for Monitoring of Natural Attenuation at IHSS 118.1 (RMRS, 1998b);
- Sampling and Analysis Plan Characterization and Conceptual Design 903 Pad/Ryan's Pit and East Trenches Plumes (IT, 1998); and
- Final Pre-Remedial Investigation of IHSS 118.1 Data Summary Report (RMRS,1997).

These and similar reports provided valuable background information for the present evaluation, although a thorough review of these documents was beyond the present scope. Data collected by the prior investigations were incorporated in the SWD dataset used in this evaluation.

# 3.1.5 Data Availability and Data Processing

Specialized, site-specific data are required to evaluate biodegradation and to develop a site-specific conceptual model of natural attenuation at the RFETS. Key analytical parameters identified in the literature include primary CAHs, daughter CAHs, metabolic byproducts, and inorganic analytes and field measurements that describe the redox environment of the groundwater. About 35 analytical and field measurement parameters are useful for the evaluations. Fortunately, at least some data were available for almost all of these analytes and the time span of data collection has been long (since 1986) at some monitoring wells.



More than 1,400 monitoring wells and piezometers have been installed at RFETS since 1954 to meet various environmental characterization and monitoring objectives. Many of these wells were installed for RCRA groundwater monitoring to characterize Operable Units (OUs) and other areas. Other wells were used to determine background concentrations of analytes, to monitor changes in the water table, to monitor for contamination at Site boundaries, or to meet other objectives.

Review of Annual Environmental Monitoring Reports (AEMRs) indicates that between 1972 and 1984 groundwater quality monitoring at RFETS was mainly concerned with radionuclides. However, the presence of CAHs in groundwater at RFETS has been known since February 1982 based on total organic halide (TOX) detections reported in Rockwell (1986). For example, during June 1983, TOX concentrations up to 3,225 µg/L were measured in groundwater sampled from well 17-74 (Rockwell, 1986). That well was located 300 feet northeast of Pond B-4.

The detection of VOCs in Site groundwater from several wells is mentioned in the 1985 AEMR (Rockwell, 1985). Widespread, periodic groundwater monitoring for VOCs at RFETS began during 1986 when 69 new monitoring wells were installed to RCRA standards. VOC data stored in SWD date from 1986 until present-day.

Varying quantities of data applic able to natural attenuation studies have been collected at a number of CAH plumes through the routine Groundwater Monitoring Program and to support accelerated remedial actions (e.g., Cowdery et al., 1998; Hopkins et al., 1998). Additional data are available from characterization of CERCLA OUs during the early 1990's. Some of the more intensely characterized areas at RFETS include IHSS 118.1 near B-771, 903 Pad and Ryan's Pit, the Mound Site, 881 Hillside in the former OU1, the East Trenches Area, and the PU&D Yard treatability study.

Since the mid-1990's, the number of wells monitored have been scaled back to meet closure objectives. Until recently, many wells within known CAH plumes at RFETS had not been sampled for VOCs for some years. During April to August 2003, the Snapshot sampling project was conducted to fill this data gap (K-H, 2003).

Because Site is currently undergoing closure and many wells are being abandoned, the Snapshot represents a final, large-scale effort to assess CAH concentrations and other water quality parameters in the IA and East Trenches areas of the RFETS. The overall objective of the Snapshot was to collect data to map the present extent of Tier I and Tier II CAH plumes in Site groundwater. An additional objective was to collect geochemical data to help define redox environments in support of this evaluation. Knowledge of redox environments (discussed later) is important in interpreting biodegradation potential. Detailed data quality objectives of the Snapshot are discussed in K-H (2003).



The Snapshot program identified 324 wells that are located in or near VOC plumes that had not been sampled for VOCs since December 31, 2000. Wells already scheduled for routine IMP groundwater sampling, with VOC analysis, during second quarter 2003 were not included in the Snapshot.

The Snapshot was designed to collect groundwater samples for VOC analysis by SW846 method 8260. The Snapshot Program also collected field parameter data at the wellhead including pH, water temperature, DO, aqueous ferrous iron, aqueous total iron, sulfide, sulfate, total alkalinity, ORP, specific conductance, and turbidity. Details of these measurements parameters may be found in K-H (2003) and in standard operating procedures referenced in that document.

Snapshot sampling crews were able to collect groundwater samples from 237 wells for partial or full suites of the parameters listed above. Seventy eight wells were found to be dry and 9 other wells were damaged or not successfully located. Water quality data generated by the Snapshot are included and interpreted in this report and are an important part of the historical groundwater quality dataset stored in SWD. Snapshot data give us a picture of the current extents and concentration ranges of CAH plumes and redox environments presently in groundwater at the RFETS.

However, most of the wells sampled were not installed for the purpose of investigating natural attenuation of CAH plumes in groundwater. Current guidance suggests that wells installed for natural attenuation studies should be closely spaced (<100 feet apart) and located along the principal contaminant flowpath (longitudinal axis) of each plume. Ideally, the line of wells should start with a local background location upgradient of the CAH source area and extend down the centerline of the plume and beyond to uncontaminated downgradient groundwater. The wells must be periodically sampled and the groundwater analyzed for CAHs, redox parameters, and other analytes that may indicate the feasibility and extent of biodegradation. Because natural attenuation processes operate slowly, many years of monitoring data are desirable.

A few relevant parameters, such as dissolved hydrogen and volatile fatty acids, have apparently not been measured in groundwater at the RFETS. Although these data would be useful, they are not critical to an evaluation of natural attenuation. Actually, the greatest weakness in the water quality dataset is that little of it was collected for the purpose of evaluating natural attenuation. Therefore, few data are available for some analytes that are keys to evaluating biodegradation.

Wells installed to meet other DQOs are not necessarily located in the correct areas to evaluate the degradation of a CAH plume as groundwater migrates downgradient from a CAH source area. Wells where groundwater was sampled to meet non-biodegradation DQOs were often analyzed for analytes not relevant to biodegradation. Another problem is that most groundwater sampling programs at the RFETS have a short duration, while biodegradation requires long periods of data collection for proper evaluation. Finally, hundreds of wells have been installed and abandoned over the course of many years at the



RFETS. Therefore, adequate well control may not exist in some areas of the RFETS during important time periods when CAH plumes developed and migrated from their source areas.

Despite the above limitations, a large historical set of analytical data has been compiled, and although it is incomplete, it is judged sufficient for this evaluation of biodegradation and natural attenuation at RFETS. The data provide intriguing glimpses into CAH degradation in specific areas of RFETS and have been used to develop a site-specific conceptual model of CAH attenuation at the RFETS.

Water quality data (analytical data) form the basis of the natural attenuation evaluations of this report. These data were retrieved from the Soil and Water Database (SWD) and processed as follows:

- RFETS Groundwater analytical results were uploaded from SWD into a local Microsoft Access
   97 database. This database and the queries used to process the data are archived on the WMCP server;
- Analyses of dissolved gases in groundwater, such as ethane and methane, were not available from SWD. These records were hand entered into an Access table and then appended to the local database;
- Analytical data were retrieved for primary samples (REAL) and field duplicate samples (DUP).
   Data for other field-originated QA/QC samples (e.g., equipment rinsates, RNS) were not retrieved. Laboratory-originated QA/QC (e.g., lab control sample) records were not retrieved;
- Data records were excluded from consideration if they were qualified as rejected (R or R1) by
  data validation or verification. Other excluded records included surrogate (SUR) compounds
  analyzed for laboratory QA/QC. Analytical results for tentatively identified compounds (TICs)
  were not of high value to the present investigation and were also excluded;
- Access queries were written to examine the data and to identify potential problems such as
  incorrect concentration units or concentration unit mismatches between the groundwater quality
  data and the action level tables that they were compared against. Several potential problems were
  identified, including the presence of nitrate data under two CAS numbers;
- Where appropriate, concentration units were standardized to μg/L;
- The data were examined for the potential presence of sample locations that were outside the area of interest or that were not relevant to the investigation, such as tanks, treatment system effluent, and most surface water stations (coded SW). Groundwater emerges at a few SW locations as seeps; these locations were included in the evaluation;
- Samples of DNAPL and multiphase mixtures of DNAPL, water, and LNAPL have been collected
  at the RFETS and the resulting analytical data are stored in SWD. Because SWD does not use a
  separate "media type code" to identify NAPL data they are stored under the groundwater (GW)
  media code. The huge concentration numbers associated with a NAPL are not representative of



solvent concentrations dissolved in groundwater and NAPL data would potentially bias the interpretation of groundwater quality data. Therefore, a search was performed in SWD comment fields to identify potential NAPL samples. RFETS personnel were also contacted to find out where and when NAPL samples may have been collected. Approximately one dozen NAPL or multiphase samples were identified; all associated with IHSS 118.1. Analytical results associated with those samples were removed from the data tables used in this evaluation; and

• Statistical outlier testing (e.g., Dixon, 1953), was not performed on the analytical data. CAH concentrations, for example, vary greatly temporally, and from well to well, and extreme values are expected near source areas. Meaningful outlier testing would have required construction of hundreds of time-series plots of the concentrations of each analyte at each well. Each plot would then need to be manually interpreted and professional judgment applied to identify and remove potential outliers.

Data validation and verification (V&V) procedures are the principal means of assessing the usability of groundwater analytical data. V&V also improves overall data quality by allowing ASD to closely monitor laboratory performance and to provide feedback to each laboratory regarding its ability to produce quality data that meets subcontract requirements. Data validation is a rigorous data review performed by a Kaiser-Hill ASD subcontractor on approximately 25% of the groundwater analytical data generated at the RFETS. The remaining 75% of the data are verified under less extensive data reviews than the validated data are subjected to. V&V criteria are generally based on government-published standards and guidelines, primarily EPA Contract Laboratory Procedures (CLP) and SW-846 method guidelines for organic and inorganic data evaluation and review.

Groundwater analytical data collected by the RFETS are considered valid (V or V1) unless the V&V process identifies analytical problems that require the data to be qualified. When it is necessary to qualify individual data records, standard qualifier codes (alphanumeric validation codes) are applied. Integer reason codes often accompany these validation codes, enabling the data user to determine why the results were qualified. For example, groundwater data with a validation qualifier R1 and a reason code 101 indicates that the verification process rejected the data as unusable for reason 101 (i.e., sample holding times were exceeded).

# 3.2 Natural Attenuation Processes and Geochemistry

Evaluation of natural attenuation processes, specifically the process of biodegradation, requires a basic understanding of the processes and how they work. The objective of this section is to provide a brief summary of the most important processes and to incorporate them into a generalized conceptual model. Geochemistry will be emphasized, particularly the geochemistry of biodegradation. This was done for the following reasons:



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- Biodegradation is widely believed to be the most important natural process in the destruction of CAHs;
- Biodegradation requires specific geochemical conditions (environments) to proceed at measurable rates; and
- When biodegradation proceeds at reasonable rates, it alters the geochemical environment in measurable ways. For example, biodegradation acts to increase concentrations of chloride and alkalinity in groundwater.

This report will interpret historical groundwater analytical data collected at the RFETS considering the above geochemical processes and environments.

# 3.2.1 Hydrologic Processes of Natural Attenuation

Although the present investigation focuses on biodegradation, additional processes are important in the natural attenuation of CAHs. The relative importance of these attenuation processes varies with the geochemistry and hydrology of each plume site. Hydrologic processes are discussed in the following paragraphs. Discussion of the geochemical processes of sorption, volatilization, and biodegradation follows in a later section.

Advection is the most important process driving contaminant migration in the subsurface. Solute transport by advection (acting alone) would carry a groundwater contaminant downgradient at a velocity that is directly proportional to the hydraulic gradient and to the hydraulic conductivity of the porous medium. Ignoring other processes, advective transport from a continuous source would produce a plume with a sharp concentration front. Upgradient of the solute front the CAH concentration would be the same as that at the source area. Downgradient of the front, the CAH concentration is zero. In nature, an advancing plume front is actually spread out by the additional processes of dispersion and diffusion. Furthermore, transport of a CAH is retarded by biodegradation and abiotic chemical reactions, as well as by sorption to the porous medium.

Hydrodynamic dispersion is the process which spreads out a contaminant plume in three dimensions, parallel to the direction of migration (longitudinal), laterally (transverse), and vertically. The underlying processes are mechanical dispersion and molecular diffusion. Mechanical dispersion is the most important at ordinary groundwater velocities and its magnitude is directly proportional to groundwater velocity and to dispersivity. Longitudinal dispersivity is a scale dependent parameter that is commonly estimated as 10% of the plume length (Fetter, 1988).

Dispersion is a mixing process caused by local variations in groundwater velocity and direction due to heterogeneities in the porous medium at microscopic to megascopic scales. The result of dispersion is



spreading and mixing at the plume edges which causes the plume front to grade from zero concentration at its downgradient leading edge with successively increasing concentrations upgradient of the edge.

Dilution reduces contaminant concentrations through groundwater recharge that adds unaffected water to the contaminated groundwater system. The most common causes of dilution are infiltration of precipitation and leakage of surface water to a shallow water table aquifer.

### 3.2.2 Geochemical Processes of Natural Attenuation

The geochemistry of natural attenuation processes is summarized to give the reader a framework for reviewing and interpreting the groundwater quality data collected at the RFETS which are discussed in Section 5. This summary also provides the necessary background for developing a conceptual model of natural attenuation.

## 3.2.2.1 Chemical Sorption and Volatilization

Sorption is a process where dissolved contaminants chemically bind to minerals or organic matter in the aquifer matrix thus decreasing their dissolved concentrations in groundwater. Desorption is the reverse process by which contaminants are released from the soil matrix increasing their concentrations in groundwater. Sorption is actually a generic term for several chemical attenuation mechanisms that will not be discussed here adsorption, coprecipitation, and precipitation. The most simplistic and widely used model of sorption and desorption assumes that they are reversible processes which can be modeled by a parameter called  $K_d$ . Sorption acts to slow the transport velocity contaminants ( $V_c$ ) relative to the velocity of the groundwater ( $V_w$ ) which is defined as  $V_c = V_w/R$ , where R is the coefficient of retardation.

At chemical equilibrium in a mixture of water and soil,  $K_d$  equals the mass of contaminant bound to the soil  $(C_s)$  divided by the contaminant concentration remaining in groundwater  $(C_g)$ , or  $K_d = C_s/C_g$ . The larger the  $K_d$  value, the greater the fraction of contaminant that will be bound to the aquifer soil, resulting in a larger retardation factor. CAHs and other organic molecules tend to bind strongly to the natural organic carbon found (in low percentages) in many sedimentary aquifer host rocks and sediments.

 $K_d$  values are specific to the contaminant of interest, to the mineralogy of the porous medium, and to the chemical composition of the groundwater. Literature values of  $K_d$  often vary over several orders of magnitude;  $K_d$  values for many analytes are strongly pH dependent.  $K_d$  values for CAHs are expected to vary in proportion to the fraction of organic matter (i.e., TOC) in the aquifer.

Volatilization is a nondestructive attenuation mechanism that removes contaminant mass from groundwater. Henry's Law describes the partitioning of a contaminant between the aqueous phase and the gaseous phase. The law is defined as  $H = C_a/C_w$ , where parameter H is the Henry's Law constant,  $C_a$ 



is the concentration in air, and C<sub>w</sub> is the concentration in water. Chemicals with H values less than 10<sup>-7</sup> atm-m<sup>3</sup>/mole are less volatile than water and their groundwater concentrations should increase as water evaporates. CAHs are much more volatile with H values ranging from a low of 0.001 atm m<sup>3</sup>/mole for 1,2-DCA to about 1.22 atm m<sup>3</sup>/mole for VC. However, the overall volatilization rate from groundwater is influenced by water table depth, soil moisture content, the presence of sorbents such as organic matter, and other environmental factors (Howard, 1989, V.I). Except for VC, and portions of plumes that are shallower than one meter, attenuation due to volatilization can generally be neglected (EPA, 1998, p.B2-26).

## 3.2.2.2 Overview of Redox Geochemistry

Understanding biodegradation processes and environmental effects requires a knowledge of redox geochemistry and nomenclature. First, redox stands for oxidation-reduction reaction. In a balanced redox reaction, an oxidizing agent (also called an oxidant or electron acceptor) gains one or more electrons from a reducing agent (also called a reductant or electron donor); the oxidant is reduced by this process. Simultaneously, the reductant loses electrons and is oxidized as the reaction proceeds.

A thermodynamically-predicted sequence of redox reactions is often observed in groundwater environments (Gurney, 1953; Lindberg, 1983). The exact Gurney sequence varies with pH. However, the general rule is that if an oxidizing groundwater and aquifer matrix were very slowly titrated with an excess of reductants, then the strongest oxidizing agent (DO) would be consumed (reduced) first. The process would continue by consuming the second strongest oxidant (usually nitrate at pH >6), then Mn(IV) aqueous and solid phases may start to reduce to Mn(II). Continued reduction may then reduce Fe(III) aqueous and solid phases to Fe(II), followed by sulfate reduction, and finally methanogenesis in which carbonic acid dissociation species are reduced to methane. Both sulfate reduction and methanogenesis require mediation by bacteria in order to proceed at measurable rates.

These reactions are characteristic of redox environments in groundwater systems. Biodegradation takes place in certain redox environments and it also geochemically alters those environments. The most direct way to recognize the redox environment of a groundwater is to look for trends in the concentrations of key reactants and products. For example, if sulfate concentrations are decreasing through time at a well, and sulfide ion (or hydrogen sulfide, H<sub>2</sub>S) concentrations are increasing, then sulfate reduction is inferred (Brady et al., 1999).

From equilibrium thermodynamics and the Nernst equation, it is possible to predict a range of Eh values characteristic of these redox reactions at a given pH. ORP measurements may be converted to Eh measurements by adding the Eh of the reference electrode to the ORP voltage. Eh-pH diagrams may be constructed which show the relative stability fields of these redox sensitive ions and solid mineral phases.



During biodegradation, as each successively weaker oxidant is reacted, the groundwater becomes more reducing, and the measured ORP or Eh should decrease. However, there are numerous difficulties with both the measurement and the interpretation of ORP and Eh data (Lindberg, 1983). For example, it is usually difficult to relate Eh measurements made by platinum electrode to a controlling redox couple, other than Fe(II)/Fe(III) in low pH, high iron waters like acid mine drainage. The O<sub>2aq</sub>/H<sub>2</sub>O couple, sulfate/sulfide, and HCO<sub>3</sub> /CH<sub>4aq</sub> redox couples are not electroactive at a platinum electrode. This means that the platinum electrode generally does not reflect the redox potential of these couples when groundwater Eh is measured.

More fundamentally, redox disequilibrium is the normal state of most groundwaters at near-neutral pH values. Redox disequilibrium means that each of the redox couples in the water is acting independently at its own Nernst potential, and consequently, there is no single Eh to measure that would be representative of the overall redox state of the water (Lindberg and Runnells, 1984).

# 3.2.2.3 Biodegradation

Numerous investigations have shown that microorganisms indigenous to groundwater environments can degrade a variety of manmade organic chemicals including chlorinated ethanes, chlorinated ethenes, chlorobenzenes, and components of gasoline, kerosene, and diesel fuel (EPA, 1998). This biologically mediated degradation is termed biodegradation and at many sites it is the most important process by which CAHs in the environment are destroyed. Therefore, an overview of biodegradation is provided below.

### 3.2.2.3.1 Overview of Biodegradation

Chemotrophic microorganisms obtain energy for growth and activity by physiologically coupling redox reactions. Under aerobic conditions, some types of bacteria couple the oxidation of organic compounds (food) with the reduction of oxygen, the strongest naturally occurring oxidizing agent found in groundwater. Under anaerobic conditions in the absence of oxygen, microorganisms may obtain less energy from weaker oxidizing agents such as PCE, TCE, nitrate, sulfate, and Fe(III). The redox potential of groundwater should decrease as oxidants and nutrients are depleted by bacteria during contaminant biodegradation. Research indicates that a succession of distinct bacterial communities grow and thrive in specific redox environments (EPA, 1998).

Biodegradation causes measurable changes in groundwater geochemistry as shown in Table 3-2. Processes are listed across the top row of the table, while analytes are listed down the left column. The expected direction of change in analyte concentration is listed in the intersecting cells as decreases or increases.



Alkalinity increases because carbon dioxide is produced by the biodegradation of organic carbon compounds. Dissolving carbon dioxide in water forms carbonic acid dissociation species. Two of these, bicarbonate ion and carbonate ion may be measured when a water is analyzed for total alkalinity. Alkalinity is increased during aerobic respiration and in all of the anoxic environments during biodegradation of CAHs and fuel hydrocarbons. Areas contaminated by petroleum hydrocarbons often have a higher total alkalinity than background areas (Wiedemeier et al., 1999).

Biodegradation of CAHs in groundwater takes place by three general mechanisms:

- Aerobic biodegradation microbial use of the organic compound as a reductant and primary substrate for growth;
- Reductive dechlorination anaerobic microbial use of the organic compound as an oxidant; and
- Cometabolism fortuitous degradation by microbes.

Under aerobic biodegradation, the primary bacterial growth substrate is also used as a reductant. Examples include fuel hydrocarbons and the less oxidized chlorinated ethenes and ethanes VC, chloromethane, and chloroethane. Under aerobic conditions (aerobic respiration), DO is coupled with these reductants. Under anoxic conditions, reductive dechlorination uses the more oxidized CAHs as oxidants, including CT, PCE, TCE, DCE, TCA, and DCA. During cometabolism, the organism gains no apparent benefit from the compound being degraded. Cometabolic degradation is a fortuitous sidereaction with microbial enzymes produced for other purposes. Further details of these three mechanisms are presented in the following paragraphs.

### 3.2.2.4 Aerobic Biodegradation of Primary Substrates

Biodegradation of fuel hydrocarbons is known to be relatively rapid under aerobic conditions; the degradation rate is limited by the availability of DO in groundwater (EPA, 1998). Microbes also perform aerobic biodegradation of the less chlorinated ethenes and ethanes, particularly VC, DCE, and 1,2-DCA. These CAH compounds act as reductants and provide organic carbon and energy to the bacteria as they are oxidized by DO. VC is the chlorinated ethene most susceptible to aerobic biodegradation. VC is oxidized to carbonic acid species. This aerobic biodegradation of VC is more rapid than other mechanisms of VC degradation, such as reductive dechlorination (RD).

Similarly, 1,2-DCA is the most susceptible chlorinated ethane because chloroethane is more likely to abiotically hydrolyze to ethanol (EPA, 1998). 1,2-DCA undergoes aerobic biodegradation to form chloroethanol which is then mineralized to carbonic acid species (Wiedemeier et al., 1999). All three isomers of DCE can be aerobically biodegraded, although cis-1,2-DCE is the most rapidly degraded DCE isomer (EPA, 1998).



Table 3-2 Geochemical Trends Produced by Biodegradation of CAHs and Fuels

Compound	Aerobic Respiration	Anaerobic Denitrification	Mn(IV) Reduction	Fe(III) Reduction	Sulfate Reduction	Methanogenesis	Reductive Dechlorination	Direct Oxidation of CAH
Fuel hydrocarbons, BTEX	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease	
CT, PCE, TCE, DCE, TCA, DCA							Parent decreases, daughter may increase initially	
VC, CM, CA	Decrease	Decrease	Decrease	Decrease				Decrease
DO	Decrease				:			•
Nitrate		Decrease						·
Mn(II)			Increase					
Fe(II)		"		Increase				
Sulfate					Decrease	May continue to decrease		
Sulfide					Increase	May continue to increase		
Chloride	Increase	Increase	Increase	Increase	Increase	Increase	Increase	Increase
Alkalinity	Increase	Increase	Increase	Increase	Increase	Increase but less obvious	. At DESIGN & Section .	Company of the second of the
Methane						Increase		
ORP, Eh	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease		

It is very important to note that the most highly oxidized CAHs with 3 or 4 chlorine atoms, e.g., PCE and TCE, resist biodegradation under aerobic conditions (EPA, 1998). This is because the highly chlorinated CAHs are already highly oxidized from the chlorine addition and do not undergo further oxidation in the presence of oxygen. Although some microbial cultures have been shown to be capable of TCE oxidation in the laboratory, Vogel (1994) observed that no strong evidence of aerobic oxidation of highly chlorinated solvents had been found at hazardous waste sites.

# 3.2.2.4.1 Anaerobic Biodegradation of Primary Substrates

Microbial respiration rapidly depletes the DO in groundwater with high organic carbon concentrations, producing anaerobic (anoxic) conditions. Bacteria can anaerobically biodegrade fuel hydrocarbons in most groundwater redox environments including denitrification, Mn(IV) reduction, Fe(III) reduction, sulfate reduction, and methanogenesis (Wiedemeier et al., 1995).

Requirements that must be met for anaerobic biodegradation of organic molecules include absence of DO, availability of a carbon source, an oxidizing agent, essential nutrients, and suitable geochemical environment, e.g., proper pH, redox potential, salinity, and temperature (EPA, 1998). Under anoxic conditions suitable oxidants may include nitrate, Mn(IV), Fe(III), sulfate, and carbon dioxide (carbonic acid species).

Although there is a large body of evidence describing the anaerobic oxidation of fuel hydrocarbons, anaerobic oxidation is not significant in degrading most CAHs because they are highly oxidized. An exception is VC which can be oxidized to carbon dioxide by Fe(III) reduction in a bacterially-mediated reaction (Bradley and Chapelle, 1997).

### 3.2.2.4.2 Reductive Dechlorination – Anaerobic Microbial Use of CAHs as Oxidants

Bouwer et al. (1981) first demonstrated that CAHs could be biodegraded in anoxic groundwater environments. This process has since been extensively investigated and is called RD. During RD, bacteria use CAHs as oxidants, rather than as carbon sources (EPA, 1998). Therefore, RD requires a separate source of carbon for bacterial growth. Potential carbon sources are fuel hydrocarbons from gasoline, diesel, hydraulic fluid, and low molecular weight organic ions and compounds like acetate, lactate, methanol, sugars, and volatile fatty acids. For this reason, leaking fuel tanks spatially associated with CAH plumes can accelerate the RD of a CAH plume. At RFETS, leaking drums of lathe coolant may undergo RD because of the hydraulic fluid mixed with the CT.

One form of RD is called hydrogenolysis, where a chlorine atom is replaced by a hydrogen atom as the parent CAH molecule is reduced. For example, *Dehalobacter restrictus* can reduce PCE and produce cis-1,2-DCE (Holliger et al. cited in EPA, 1998).



Recent studies have also discovered direct dechlorinators, bacteria that can use chlorinated ethenes (PCE and TCE) as oxidants and apparently as carbon sources in a process called dehalorespiration. There is also evidence that dechlorination may be dependent on the supply of dissolved hydrogen acting as the reductant. The hydrogen source results from microbial degradation of a primary substrate (e.g., acetate, ethanol, and fuel hydrocarbons).

In anaerobic environments, the more highly chlorinated compounds CT, PCE, TCE, DCE, TCA, and DCA may be used as oxidants. They are reduced in microbially-mediated reactions to less chlorinated daughter products. The parent concentration decreases and the daughter concentration initially increases, subsequently decreasing as it is later consumed (Appendix I). This produces chemical decay chains like  $PCE \rightarrow TCE \rightarrow DCE \rightarrow VC \rightarrow$  ethene. However, because of the relatively low oxidation state of VC, it more commonly undergoes aerobic biodegradation as a primary substrate near the plume edge, instead of RD (EPA, 1998).

PCE and TCE can be anaerobic ally reduced to 1,1-DCE, cis-1,2-DCE, or trans-1,2-DCE, although cis-1,2-DCE is the more common degradation (or daughter) product (Bouwer, 1994). The least common product is 1,1-DCE.

Geochemical indicators of RD of CAHs include (EPA, 1998):

- DO concentrations are low or not detected;
- Detectable ethene, ethane and/or methane is present;
- Fe(II) is being produced (locally increasing aqueous concentrations); and
- Dissolved hydrogen concentrations are between 1 and 4 nanomolar (10<sup>-9</sup> molar).

#### 3.2.2.4.3 Cometabolism of CAHs

Biodegradation of a chlorinated solvent by cometabolism occurs without involving the CAH as a carbon source or an oxidant. Bacterially-produced oxygenases are often nonspecific enzymes that fortuitously support oxidation of many CAHs (McCarty and Semprini, 1994). In some cases, RD may be a cometabolic process that results in slow and incomplete dechlorination (EPA, 1998). Cometabolism of CAHs is best documented in aerobic environments. Cometabolism is a less important degradation process than RD.

### 3.2.2.5 Abiotic Degradation of CAHs

Abiotic chemical transformations such as hydrolysis, slowly convert some CAHs into simpler molecules. Hydrolysis refers to the direct reaction of a CAH molecule with water. An important example is the



hydrolysis of 1,1,1-trichloroethane to form acetic acid. This process is relatively rapid, with a hydrolysis half-life of 0.5 to 1.7 years (Vogel et al., 1987). Chloride ion is released to groundwater and the generated acetate ions are consumed by bacteria or are oxidized to carbonic acid dissociation species, such as bicarbonate ion.

A second example is the hydrolysis of chloroethane to form ethanol. Hydrolysis is very rapid with a chloroethane half-life of 0.12 years (Vogel et al., 1987). In general, monochloroalkanes hydrolyze with half-lives of about one month, while polychlorinated molecules hydrolyze at a slower rate (i.e., have a longer half-life). CT slowly hydrolyzes with a half-life of 41 years, while its daughter CF requires 3,500 years (Wiedemeier et al., 1999).

Dehydrohalogenation is another abiotic aqueous chemical reaction in which a chlorinated alkane eliminates HCl to produce a less chlorinated alkene. An example is 1,1,1-TCA giving up HCl to form 1,1-DCE. The half-life of 1,1,1-TCA in this reaction is 0.8 to 2.5 years (Vogel et al., 1987). The dehydrohalogenation reaction rate increases with the number of chlorine atoms attached to the carbon atom that eliminates a chlorine.

Whether abiotic or microbiological, the degradation of CAHs in nature proceeds from the more chlorinated and more oxidized parent compounds, to the less chlorinated, less oxidized, and molecularly simpler daughter products. Complete dechlorination results in simple alkanes (methane, ethane), alkenes (ethene), or alcohols (methanol, ethanol), or oxidation to carbon dioxide, water, and chloride ion.

Figure 3-4 summarizes potential degradation pathways from the literature. Common chlorinated solvents form the top two rows. Proceeding down a path from top to bottom, each parent compound is losing one or more chlorine atoms, forming a daughter product while increasing the chloride ion concentration in groundwater. The parent solvents tend to be the most hydrophobic, most strongly sorbed (highest  $K_{ow}$ ), and least soluble in groundwater. Therefore, the compounds at the top of Figure 3-4 are strongly retarded (least mobile). Moving down the figure, the daughters tend to become less strongly sorbed, increasingly mobile, and increasingly soluble in groundwater, as they become less hydrocarbon-like. This is illustrated by the following log  $K_{ow}$  and solubility data from Howard (1990) for the carbon tetrachloride decay series (Table 3-3). However, this relationship is not perfect because the solubility of chloromethane should be greater than that of methylene chloride.

Table 3-3 Carbon Tetrachloride Family Octanol-Water Distribution Coefficients and Solubility

САН	Log K <sub>ow</sub>	Aqueous Solubility (mg/L)		
Carbon tetrachloride	2.83	805		
Chloroform	1.97	7,950		
Methylene chloride	1.25	13,000		
Chloromethane	0.91	6,480		



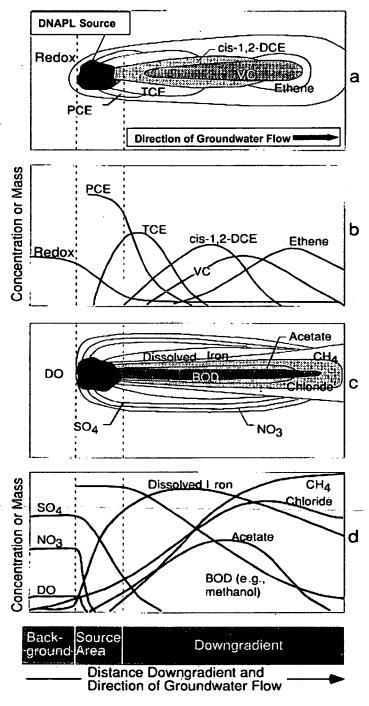
Oxic Groundwater 1,1,1,2-PCA PCE Anoxie Graundwaiei CT 1,1,2-TCA **TCE** 1,1,1-TCA trans-1,2-DCE cis-1,2-DCE 1,1-DCE МС 1,1-DCA 1,2-DCA Sulfate Reduction VC CA СМ CH, Production **ACETIC ACID ETHANOL METHANOL** CHOLOROETHANOL **METHANE ETHENE ETHANE** ....CO2 + H2O \_

Figure 3-4 Anoxic Degradation Pathways of Chlorinated Aliphatic Hydrocarbons

The diagram based on data from Vogel, Criddle, and McCarty (1987), EPA (1998), Bouwer (1994), Vogel (1994), McCarty and Semprini (1994), Brady et al. (1999), and Wiedemeier et al. (1997).



Figure 3-5 General Conceptual Model of Biodegradation of a PCE Contaminant Source in a Type I Anaerobic Environment with Fuel Hydrocarbons



Adapted from Wiedemeier et al. (1999).



# 4 SETTING, CONTAMINANT RELEASES, AND PREVIOUS NATURAL ATTENUATION WORK

This section describes the physical and hydrogeologic setting of the RFETS IA and of adjacent land with groundwater contaminated by chlorinated solvents.

## 4.1 RFETS Industrial Area and Surroundings

The IA is located near the center of the 10 square mile RFETS plant site. It dates back to 1951 when construction began on the nuclear weapons processing plant northwest of Denver.

## 4.1.1 Physical and Industrial Setting

The IA contained all of the important processing buildings, waste storage areas, and waste treatment facilities (Figure 4-1). Almost all CAH contamination in groundwater at RFETS is found within the IA or immediately east of the IA in the Mound and East Trenches Areas. Several CAH plumes are located on the south flank of the IA or appear to have migrated southwards from the IA towards Woman Creek.

No CAH plumes are presently known to exist in Buffer Zone groundwater. Therefore, this report uses the term Site-wide to refer to the IA and surrounding area between Walnut Creek on the north and Woman Creek on the south. This Site-wide area is shown on Figure 3-1 and extends eastward past the East Trenches to Pond B-5. CAH plumes have not been detected west of 1<sup>st</sup> Street which is used as the western boundary of site-wide figures in this report.

## 4.1.2 Hydrogeology

The hydrogeology of the RFETS has been presented in numerous reports and only a brief description is presented here. Most of the groundwater data evaluated in this report were obtained from the upper hydrostratigraphic unit (UHSU) which is the uppermost saturated stratum beneath the site. This unit is composed of unconsolidated gravel, sand and silt of the Rocky Flats Alluvium, Colluvium, and Valley Fill Alluvium. Below the alluvium, the UHSU also includes a zone of weathered bedrock developed on top of the Arapahoe Formation bedrock. Locally subcropping porous sandstone units (the No. 1 Sandstone) of the Arapahoe Formation are also included within the UHSU.

The Rocky Flats Alluvium thins from west to east across the IA and caps the pediment surface beneath the IA. Colluvium and slump deposits are found on the hill slopes overlooking the stream drainages. Valley Fill Alluvium occurs in the bottom of the stream drainages.



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Unconfined groundwater is present within the UHSU across the IA and eastwards across the East Trenches area. The water table elevation varies seasonally and from year to year. In local areas, the UHSU may be unsaturated on a seasonal basis or during dry years.

Figure 4-2 shows a potentiometric map of the UHSU water table during the 2<sup>nd</sup> quarter of 2002. Although the water table is locally influenced by nearby building drains, the potentiometric contours generally parallel surface topography as expected for a water table aquifer. Groundwater flow directions are downgradient and perpendicular to the water table contours. Groundwater flow in the IA is generally towards the east and towards the Walnut and Woman Creek drainages.

The red lines on Figure 4-2 were used to estimate Darcy groundwater velocities in the Final RFCA Annual Groundwater Monitoring Report for 2002 (K-H, 2004). For consistency, some of these velocities were used to estimate bulk attenuation rate constants.

## 4.1.3 Usage of Chlorinated Aliphatic Hydrocarbons (CAHs) at RFETS

The parent CAHs (e.g., CT and PCE) in groundwater are of manmade origin and usually entered soil and groundwater from leaking solvent tanks, leaking drums, accidental spills, or historical waste disposal practices. However, TCE may either be manmade or a daughter product of the biodegradation of PCE.

Similarly, CF and MC are both manmade solvents as well as decay products of the reductive dechlorination of CT. Therefore, distinguishing the origins of many of the CAHs detected in groundwater at the RFETS is central to an evaluation of the extent of natural attenuation. Consequently, it is important to summarize which manmade CAHs were used at the RFETS, where and when they were used, and in what quantities. At the RFETS, most releases of CAHs to the environment probably took place during the 1950's and 1960's. However, widespread groundwater quality monitoring did not start at the RFETS until 1986, although 138 wells are known to pre-date 1986. Groundwater sampled from these older wells was apparently monitored for radionuclides.

The following sections discuss available historical data on many of the CAHs found in the RFETS groundwater.

## 4.1.3.1 Carbon Tetrachloride

Rocky Flats Plant (RFP) was formerly the largest volume user of CT in the United States (ChemRisk, 1992). The 1974 Harmful Materials Inventory listed 12,500 kg of CT on plant site, while the 1988-1989 inventory listed 7,060 kg. CT was used in numerous industrial processes at the RFETS including:



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Cleaning weapons components, machinery, instruments, furnaces, and glove boxes;

- Chip degreasing and briquetting of Pu metal and to wash Pu lathe turnings; and
- Laboratory scale solvent extraction operations.

Air Pollution Emission Notice Reports (ChemRisk, 1992) provide a rough estimate of the areal distribution of CT usage (based on CT air emissions) at RFETS as follows:

•	B-707	80%;
•	B-777	14%;
•	B-776	6%;
•	B-460	1%; and
•	B-881	1%.

Solubility calculations may provide clues to the locations of unknown or poorly known NAPL sources and clues for determining the mixture of solvents that may have been spilled. Such calculations are simple estimates based on the water solubility of each pure CAH at room temperature. In reality, if a mixture of several chemicals was spilled, then the aqueous solubility of each compound in the mixture would be lowered by multiplying the solubility of the pure compound times its mole fraction. Thus, simplified solubility calculations reported here may underestimate the actual percent solubility of CAHs associated with mixed sources.

Historical analyses of CAHs in groundwater were retrieved from SWD and compared against the published solubility of each compound in pure water. Percent solubility was computed at each well and descriptive statistics calculated. Because a CAH source area requires many years to degrade, and wells were installed and sampled over a range of years, the solubility data were time-averaged to yield the maximum spatial coverage.

Time-averaged, mean percent (%) solubility calculations were performed for CT in groundwater. The results are shown on Figure 4-3 and indicate indicates that up to 4.4% of CT solubility may occur at the Site. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area (Brady et al., 1999). Areas with greater than 1% CT solubility are restricted to the 903 Pad where CT in lathe coolant was stored in drums and IHSS 118.1 south of B-771 where reported spills were associated with a large tank of CT. Thus, the solubility mapping has some merit, although it likely misses many small sources of DNAPL with no nearby monitoring wells.



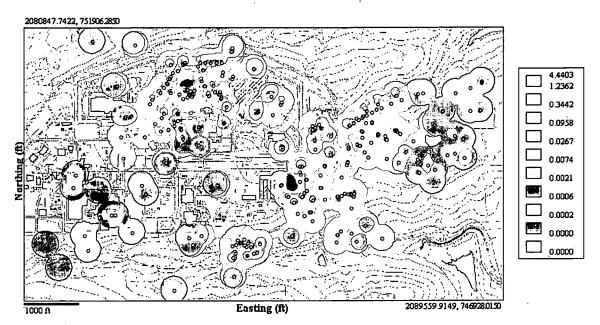


Figure 4-3 Map of Time-Averaged, Mean Percent (%) Solubility of Carbon Tetrachloride

#### 4.1.3.2 Tetrachloroethene

PCE was widely used for degreasing and cleaning operations in many of the RFP buildings (ChemRisk, 1992). The PCE inventory at the RFP during 1974 was 4,462 kg. By 1989 the PCE inventory was only 1.5 kg. It is believed that during the 1970's PCE was replaced by 1,1,1-TCA.

PCE was most heavily used in B-881 prior to 1963 where 50 drums per month were used in enriched uranium processing (ChemRisk, 1992). PCE was used in B-886 between 1965 and 1975. PCE was also widely used in buildings B-889, B-886, B-883, B-881, B-776, B-771, and B-444. PCE air emissions estimates were not available for most of these buildings prior to 1992.

Circa 1992, the most significant PCE waste stream source was B-889, although 100% of PCE air emissions were from B-374 (ChemRisk, 1992). PCE was present in liquid wastes treated in B-374 and was emitted during waste neutralization.

Time-averaged, mean percent (%) solubility calculations were performed for PCE in groundwater. The results are shown on Figure 4-4 and indicate indicates that up to 4.2% of PCE solubility may occur at the Site. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area (Brady et al., 1999). Areas greater than 1% PCE solubility are restricted to the Mound Site and possibly the 903 Pad.



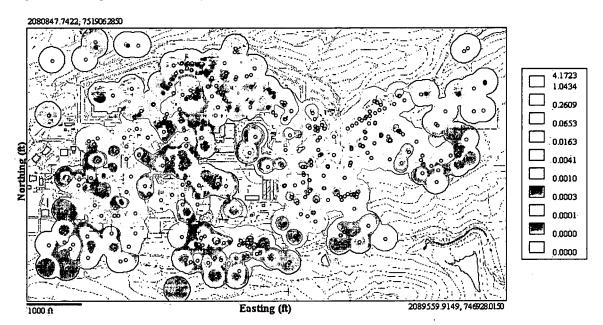


Figure 4-4 Map of Time-Averaged, Mean Percent (%) Solubility of Tetrachloroethene

#### 4.1.3.3 Trichloroethene

TCE was used in large volumes at the RFP to clean and degrease weapons components made of Be, U, and Pu. TCE was used in vapor degreasers at plant starting in 1963 when it replaced other solvents (ChemRisk, 1992). TCE use at the RFP during 1973 was about 10,000 gallons. During 1974, the inventory of TCE at the RFP was 22,763 kg (ChemRisk, 1992). By 1989, most TCE usage was replaced by other solvents (e.g., 1,1,1-TCA) and the TCE inventory decreased to 140 kg.

Like PCE, TCE was heavily used in B-881 prior to 1963. TCE was used to clean glove boxes in B-771 prior to the introduction of KW soap during the 1960's. Small volumes of TCE were also used in B-460. The most significant TCE waste stream, circa 1992, was B-889, although 100% of TCE air emissions were from B-374 (ChemRisk, 1992). TCE was present in liquid wastes treated in B-374 and was emitted during waste neutralization.

Time-averaged, mean percent (%) solubility calculations were performed for TCE in groundwater. The results are shown on Figure 4-5 and indicate indicates that up to 6.4% of TCE solubility may occur at the Site. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area (Brady et al., 1999). Areas greater than 1% TCE solubility are restricted to the Ryan's Pit, the East Trenches area, and possibly the 903 Pad. These are all plausible locations for the presence of DNAPLs containing TCE.



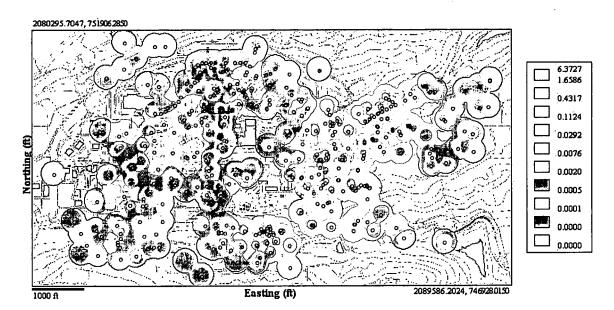


Figure 4-5 Map of Time-Averaged, Mean Percent (%) Solubility of Trichloroethene

## **4.1.3.4 1,1,1-Trichloroethane**

The inventory of 1,1,1-TCA at the RFP during 1974 was 22,763 kg (ChemRisk, 1992); its inventory in 1989 was 1,750 kg. Use of 1,1,1-TCA during 1977 was estimated at 4,675 gallons (DOE, 1980). This chlorinated solvent was used in cleaning and vapor degreasing of U and Pu parts. It was also used as a cutting agent in the machining of Pu. During the 1970's, the RFP used 1,1,1-TCA as a replacement for TCE and PCE. 1,1,1-TCA remained in use until May 1990 for cleaning parts during assembly work.

Air emissions estimates by ChemRisk (1992) suggest the following 1980's distribution of 1,1,1-TCA usage at the RFP:

•	B-777	31%	B-774	31%;
•	B-776	29%	B-707	14%;
•	B-881	1%	B-460	1%; and
•	B-374	1%.		

Time-average, mean percent (%) solubility calculations were performed for 1,1,1-TCA dissolved in groundwater. The results are shown on Figure 4-6 and indicate that up to 6.3% of 1,1,1-TCA solubility may occur at the Site. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area (Brady et al., 1999). Areas greater than 1% 1,1,1-



TCA solubility are restricted to IHSS 118.1 south of B-771 and to 881 Hillside (formerly OU1) where known 1,1,1-TCA spills are known to occur.

Figure 4-6 Map of Time-Averaged, Mean Percent (%) Solubility of 1,1,1-Trichloroethane

## 4.1.3.5 Chloroform

CF (or trichloromethane) is the first daughter product formed during natural biodegradation of CT. However, CF is also a manmade solvent, a volatile heavy liquid at room temperature. The 1974 harmful materials inventory listed 5,513 liters of CF at RFETS (ChemRisk, 1992). The 1989 inventory listed 500 kg of chloroform. Known uses of chloroform at RFETS included the following:

- B-334 used as a solvent and adhesive;
- B-460 used to cement Plexiglas;
- B-559 used as an extractant in analyzing the gallium (Ga) content of Pu samples; and
- B-881 dissolution of photo resists and plastics.

The principal CF air emissions appear to have been from the B-559 laboratory (ChemRisk, 1992). CF was also released during neutralization of liquid process wastes in B-374.

Time-average, mean percent (%) solubility calculations were performed for CF dissolved in groundwater. The results are shown on Figure 4-7 and indicate that no CF solubilities exceeded 0.26%. The highest percent solubility areas are at IHSS 118.1 and at 903 Pad. Because the mapped solubilities of CF are



considerably less than 1%, this suggests that CF is a daughter product of CT degradation rather than one of the primary solvents used at the Site.

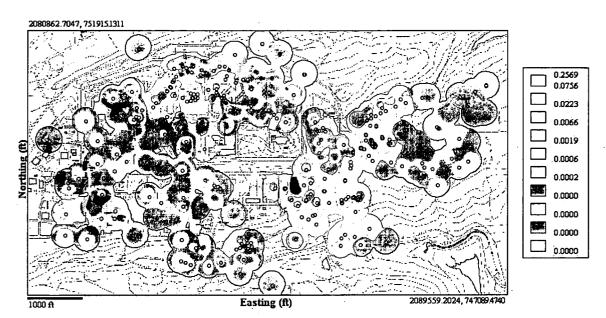


Figure 4-7 Map of Time-Averaged, Mean Percent (%) Solubility of Chloroform

## 4.1.3.6 Methylene Chloride

Chemical inventory data was not found for MC use at the RFP. However, significant use of MC occurred in B-889 during the 1960's and 1970's for clean-up of oralloy line equipment (ChemRisk, 1992). Known uses of MC at the RFP included:

- B-374 Treatment of liquid process wastes;
- B-460 An ingredient of the Cee Bee solution used in the aqueous component cleaning line;
- B-771 Found in paints and paint strippers;
- B-776 Present in wet wastes; and
- B-881 Used in several laboratories and process areas for sample preparation.

Time-average, mean percent (%) solubility calculations were performed for MC in groundwater. The results are shown on Figure 4-8 and indicate that no MC solubilities exceeded 0.09%. The most elevated MC concentrations are at or near the 903 Pad where it's probably a daughter of CT biodegradation. These low observed solubilities suggest that MC use at the RFP was not of sufficient volume to result in NAPLs in the UHSU.



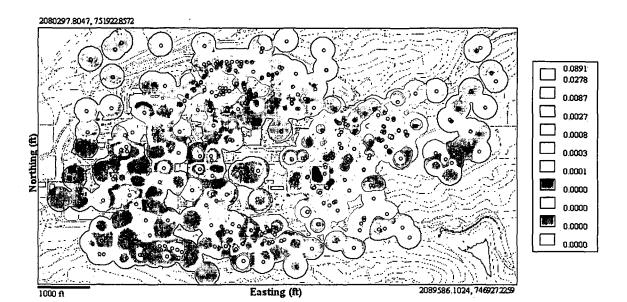


Figure 4-8 Map of Time-Averaged, Mean Percent (%) Solubility of Methylene Chloride

## 4.2 Plume Signature Areas

The seven PSAs of special interest to VOC fate and transport modelers were selected for natural attenuation evaluation. Existing information about each of these PSAs is summarized in the following sections and are shown on Figures 3-2 and 4-1. The PSAs are outlined by rectangular boundaries. Each boundary encloses a CAH source area, a small upgradient background area, and a larger downgradient area that contains the plume. The maximum areal extent of the PSA boundaries is subjective but they are intended to minimize the influence of adjacent plumes while maintaining boundaries that are oriented north-south or east-west. These orientations facilitate both map-making and database queries.

## 4.2.1 PSA2

PSA2 includes the 903 Pad Plume area. The 903 Pad Plume originates at the 903 Pad, flows east, then splits and flows both northeast and southeast. This report focuses on the southeast portion of the CAH plume on the hillside overlooking Woman Creek.

## 4.2.1.1 Description and Setting

The 903 Pad sits in a flat area in the southeast corner of the IA (Figure 4-9), south of Central Avenue and between the 904 Pad and the Southeast Perimeter Road.



#### 4.2.1.2 Local Hydrogeologic Influences and Variations

Because the 903 Pad is located at the top of the hillside overlooking Woman Creek, some groundwater leaves the pad and flows south or southeast down the hillside towards the creek. Plume maps of this area show a flow divide that directs much of the plume leaving the Pad to the east and northeast.

#### 4.2.1.3 Historical Releases of Solvents and Fuels

Between 1958 and 1967 about 5,240 drums of Pu and U-contaminated oil were stored at the 903 Pad area (ChemRisk, 1992). Most of these waste oils came from B-776, B-881 and B-444. Corroded and leaking drums lead to soil contamination by Pu. The contents of the corroded drums were repackaged for transport to B-774 for solidification. Pu-contaminated coolant was in 3,572 of the repackaged drums.

# 4.2.1.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

Pu soil contamination at the pad was covered by fill and asphalt in November 1969. Partial removal of a highly contaminated subsurface area was reported during the mid-1980's. Recently, during 2003, surficial soils were removed from the pad area. No accelerated groundwater remedial actions have been performed in this area to date.

## 4.2.2 PSA3

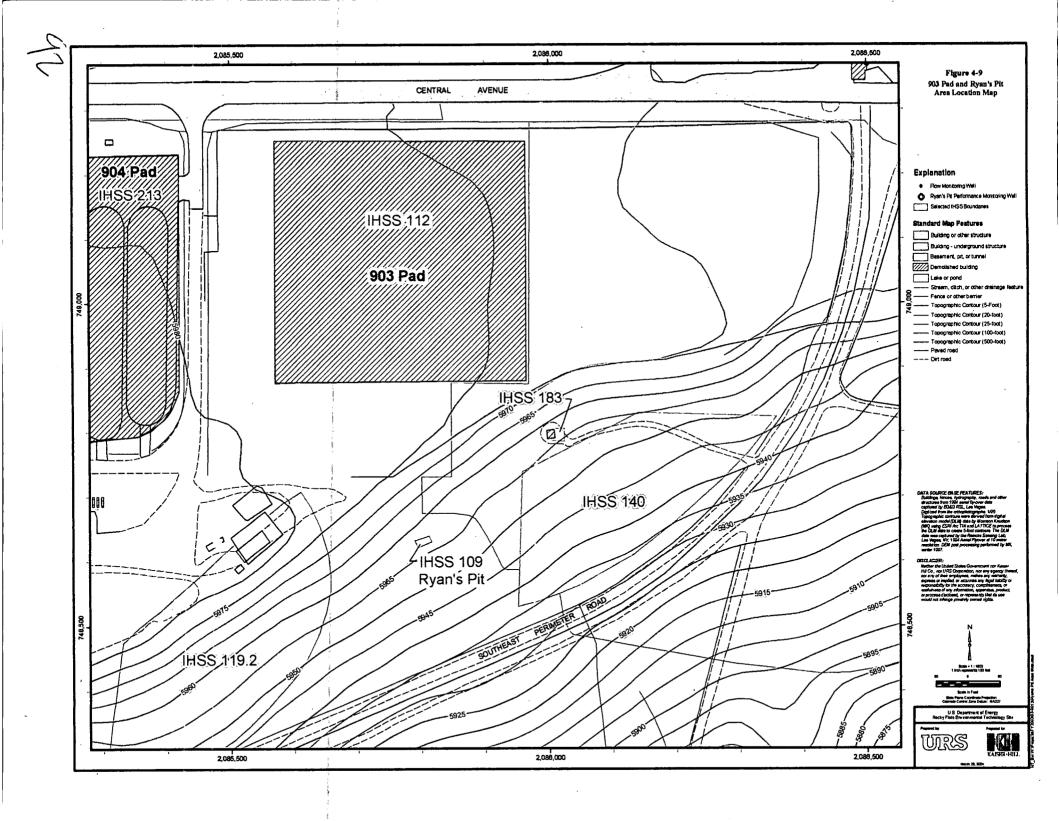
PSA3 includes the Ryan's Pit plume that is sourced from IHSS 109. This area was part of the former OU2.

# 4.2.2.1 Description, Local Physical and Industrial Setting

Ryan's Pit is located about 100 feet southeast of the southeast corner of the 903 Pad (Figure 4-9). Ryan's Pit is about 20 feet long by 10 feet wide by 5 feet deep. Because of the proximity of Ryan's Pit on the hillside south of the 903 Pad, this evaluation assumes that the areal extent of PSA3 is identical to that of PSA2.

#### 4.2.2.2 Local Hydrogeologic Influences and Variations

Although Rocky Flats Alluvium is present beneath the 903 Pad, the alluvium does not extend down to Ryan's Pit. The Ryan's Pit area is underlain by clay-rich colluvium and reworked Rocky Flats Alluvium. The Arapahoe No.1 Sandstone subcrops under the alluvium southeast of the 903 Pad beneath the 903



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Pad/Ryan's Pit plume (RMRS, 1999b). This sandstone has a relatively large hydraulic conductivity and may affect contaminant transport from Ryan's Pit. Caliche is common in these alluvial deposits at Ryan's Pit. Slump features are present in this area, including a large scarp face between the 903 Pad and Ryan's Pit (RMRS, 1999b).

The contaminant plume from Ryan's Pit is primarily confined to the UHSU (RMRS, 1999b). Groundwater beneath Ryan's Pit hillside flows down-slope to the south or southeast towards Woman Creek. The volume of groundwater for contaminant transport is limited because of higher evapotranspiration on the south-facing slope (RMRS, 1999b). Contaminated groundwater in wells 01298, 01498, and 01698 may eventually discharge to the South Interceptor Ditch and/or to Woman Creek (RMRS, 1999b, p.10).

#### 4.2.2.3 Historical Releases of Solvents and Fuels

Since 1969, Ryan's Pit was a waste disposal site. During 1971, the pit received non-radioactive liquid wastes including PCE, TCE, CT, and paint thinner or kerosene (RMRS, 1999b).

# 4.2.2.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

One hundred and eighty cubic yards of contaminated soil and degraded drums were removed from Ryan's Pit during September 1995. The soils were treated in February 1996 and the decontaminated soils were replaced in August 1996 (RMRS, 1999b). Free phase PCE and motor fuel constituents were found during the removal action (RMRS, 1999b).

#### 4.2.3 PSA5

PSA5 includes the Mound Site Plume area located on the east side of the IA.

## 4.2.3.1 Description and Setting

The Mound Site Plume is located north of Central Avenue and east of the southeast corner of the former Protected Area (PA). The Mound Site (IHSS 113) was a drum storage area located north of the 903 Pad (Figure 4-10). Between April 1954 and September 1958, 1,045 drums of oil and solid waste were buried at the site (ChemRisk, 1992). During March and April 1957, 169 drums of uranium-contaminated oil were burned there. After September 1958, oil and coolant drums were moved to the Mound area but were not buried. The drums were removed in May 1970.



## 4.2.3.2 Local Hydrogeologic Influences and Variations

The Mound Site is located near the southern edge of the South Walnut Creek drainage basin. Surficial deposits beneath the site consist of about 12 feet of Rocky Flats Alluvium, colluvium, and slump deposits with some artificial fill and disturbed soil (RMRS, 1998). Underlying the surficial material is weathered claystone of the Arapahoe and Laramie formations. The Arapahoe No. 1 Sandstone subcrops beneath the alluvium at the northeast corner of the Mound Site. The subcrop area contains a number of intermittent seeps above the South Walnut Creek drainage.

Depth to groundwater fluctuates in this area. The unconsolidated materials are dry most of the year, but groundwater levels can reach within 3 to 6 feet of ground surface during the wet season. The VOC plume in Mound Site groundwater extends north from the site and discharges as seeps and subsurface flow into the South Walnut Creek drainage near the seep at sampling station SW059 (RMRS, 1998). VOC-contaminated groundwater has been found in the No. 1 Sandstone and in alluvium and colluvium. Groundwater appears to flow primarily along the top of the weathered bedrock surface.

#### 4.2.3.3 Historical Releases of Solvents and Fuels

The Mound Site was a drum storage area between 1954 and 1958 that stored 1,405 drums mostly of U-, Pu-, and Be-contaminated lathe coolant and some drums of PCE (RMRS, 1998). The drums were removed in 1970 when it was estimated that 10% of the drums had leaked (RMRS, 1998). There are no records of the volume of contaminants leaked to the soil. However, 140 drums of 55-gallon capacity could spill a maximum of 7,700 gallons of liquid, of which about 70% may have been hydraulic oil (5,400 gallons), and 30% carbon tetrachloride (2,300 gallons).

ChemRisk (1992) inventoried the contents and source of wastes in approximately 1,600 drums that were located at the Mound Site. The inventory included:

- 1,298 drums of oils, stillbottoms and perclene (PCE) from B-444;
- 89 drums of oils with carbon tetrachloride from B-776;
- 46 drums of oils with carbon tetrachloride from B-771;
- 85 drums of oils from B-881; and
- 88 drums of dry waste from B-991 and B-441.



# 4.2.3.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

Source area soils contaminated by VOCs were removed from the Mound Site in 1997. Radioactively contaminated soils were previously removed (RMRS, 1998). Thirty-five VOC compounds have been detected in the Mound Site Plume, but PCE is the predominant contaminant, historically reaching 528 mg/L in groundwater at well 0174. The reported highest TCE concentration was 18 mg/L (RMRS, 1998).

The Mound Site Plume Treatment System (MSPTS) is located north of the Mound site (Figure 4-1). The MSPTS uses a reactive zero valent iron barrier to destroy chlorinated organic compounds and immobilize low activities of uranium. The MSPTS was installed in 1998 and uses a 220-foot long groundwater collection system that funnels water to two treatment cells.

During 2001, influent and effluent sampling and analysis demonstrated that the MSPTS is effectively removing the CAHs in the groundwater treated by the system. These data are summarized in Table 4-1 (K-H, 2002a). Naturally occurring biodegradation may be occurring upgradient of the treatment system as indicated by the presence of the PCE daughter products, TCE and cis-1,2-DCE. Similarly CF and MC are daughter products of the degradation of CT.

Table 4-1 Influent and Effluent Chemistry at the Mound Treatment System During 2001

САН	Influent Groundwater Concentration Range (µg/L)	Reactor 2 Effluent Concentration Range (µg/L)
PCE	44 to 50	Not detected
TCE	74 to 76	Not detected
cis-1,2-DCE	23 to 38	0.26 to 3
СТ	73 to 130	Not detected
CF	20 to 23	Not detected to 0.6
MC	Not detected	Not detected to 6
1,1,1-TCA	3.4 to 4	Not detected

## 4.2.4 PSA7

PSA7 includes the East Trenches plume south of Ponds B-2 and B-3.



## 4.2.4.1 Description, Local Physical and Industrial Setting

Unlike plumes in the IA, there are no large buildings or paved parking lots in the East Trenches area. A number of shallow waste disposal trenches were dug east of the IA and filled with drums or other industrial wastes. Chlorinated solvents migrated from some of these trenches forming the East Trenches Plume. Figure 4-10 shows the locations of trenches T-3 through T-11. These trenches are labeled with their IHSS numbers 110 and 111.1 through 111.8.

### 4.2.4.2 Local Hydrogeologic Influences and Variations

CAH plumes originating in the East Trenches area are potentially commingled with CAH plumes migrating northeastwards from the 903 Pad and potentially from the Mound Site.

RMRS (1999a) states that "the Arapahoe No.1 Sandstone is present beneath the East Trenches source area and is a preferential flowpath for contaminated groundwater to migrate towards South Walnut Creek." This sandstone is also present at the distal end of the plume and subcrops in the colluvium above South Walnut Creek. The sand is believed to carry most of the contaminant flux north or northeast towards the creek. This groundwater discharges as seeps on the hillside above the creek or migrates through the Valley Fill Alluvium that underlies the creek.

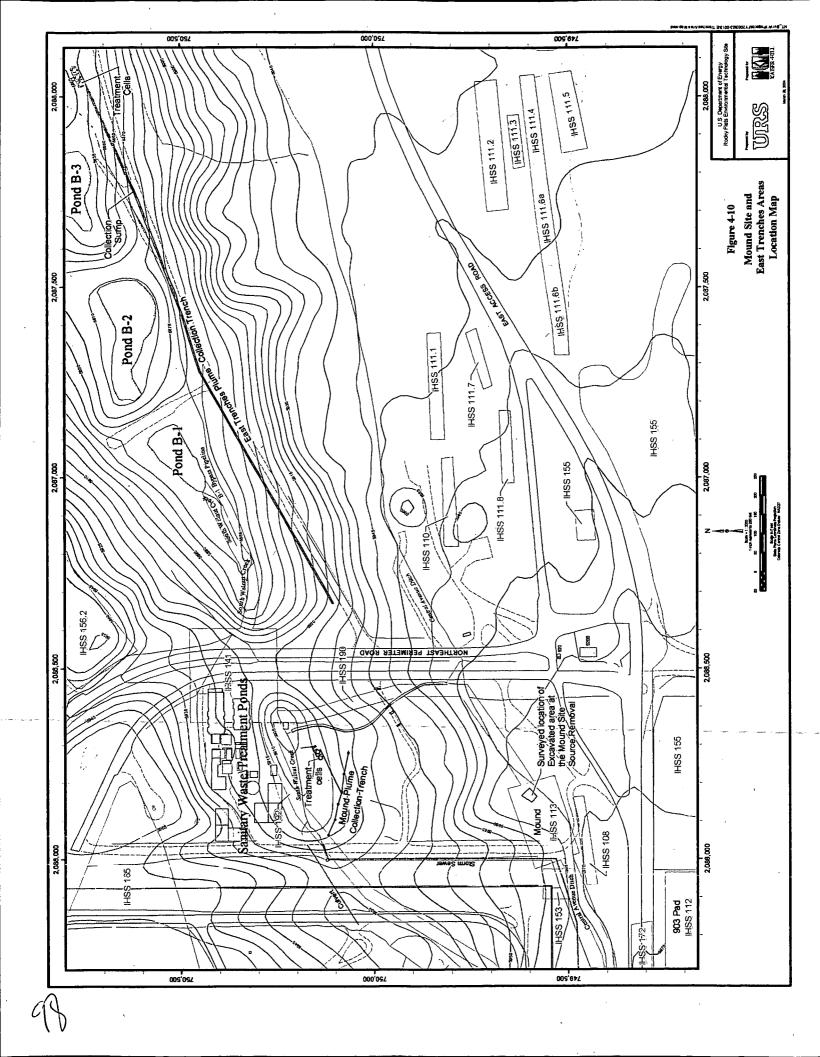
The hydraulic gradient is northwards at 0.14 ft/ft in the vicinity of well 23697. Geometric mean hydraulic conductivities in the East Trenches Area are 7.9E-4 cm/sec in weathered Arapahoe No.1 sandstone; 2.1E-4 in weathered Arapahoe/Laramie sandstones other than the No.1 Sand; 9.3E-5 cm/sec in colluvium; 9.98E-7 cm/sec in weathered Arapahoe/Laramie claystone (RMRS, 1999a).

Surface water sampling of Pond B-2 during February 1998 found 400  $\mu$ g/L TCE; 100  $\mu$ g/L cis-1,2-DCE; 18  $\mu$ g/L CT; 14  $\mu$ g/L CF; and 16  $\mu$ g/L PCE (RMRS, 1999a). Seep water above Pond B-2, SW00298, was also analyzed during this period and contained 120  $\mu$ g/L PCE; 970  $\mu$ g/L TCE; 32  $\mu$ g/L cis-1,2-DCE; 98  $\mu$ g/L CT; and 30  $\mu$ g/L CF.

## 4.2.4.3 Historical Releases of Solvents and Fuels

Trenches T-3 (IHSS 110) and T-4 (IHSS 111.1) were located 300 to 600 feet east of the East Perimeter Road and several hundred feet north of the East Access Road. These trenches were used between 1964 and 1967 for disposal of crushed drums, VOCs, and sewage sludge containing low level Pu and U (RMRS, 1999).





04-RF-00358

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The main contaminants in the East Trenches groundwater plume are VOCs from the T-3 and T-4 source areas. Petroleum compounds, semivolatile organics, and U-238 were also detected in the source area (RMRS, 1999).

# • 4.2.4.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

The primary source area for the East Trenches plume was excavated as part of an accelerated action in 1996 (RMRS, 1999). Soil and debris removed from the trenches was treated by thermal desorption to remove the VOCs, which were mainly CT, TCE, and PCE. Treated soil that was below Tier II action levels was returned to the excavation and the area was revegetated. Radiologically-contaminated soils with activities below Tier I were wrapped in geotextile material and re-buried in the T-4 excavation (RMRS, 1999).

The East Trenches Plume Treatment System (ETPTS) was installed in 1999 and consists of a 1,200 foot long groundwater collection system and two zero valent iron reactive treatment cells (K-H, 2002a). These cells use zero valent iron to destroy CAHs in the influent groundwater. The ETPTS is located south of the B-series ponds and north of the East Trenches Plume area (Figure 4-10).

During 2001, K-H (2002a) indicated that the main contaminants in the influent water included TCE (2,500 to 2,900  $\mu$ g/L); PCE (240 to 350  $\mu$ g/L); CT at 160  $\mu$ g/L; CF at 79 to 84  $\mu$ g/L; and cis-1,2-DCE (up to 32  $\mu$ g/L). The ETPTS effectively removed these VOCs from the effluent groundwater.

#### 4.2.5 PSA10

PSA10 includes the CAH plume found in the B-444/B-460 area. This plume generally migrates to the southeast.

#### 4.2.5.1 Description and Setting

PSA 10 is located near B-460, B-444, and B-664. These buildings are located in the southwestern IA. Manufacturing of stainless steel parts was performed at B-460.

## 4.2.5.2 Local Hydrogeologic Influences and Variations

An east-west trending groundwater flow divide crosses the north end of PSA10. UHSU groundwater located south of this divide generally flows southeast towards Woman Creek.

100

#### 4.2.5.3 Historical Releases of Solvents and Fuels

B443 was formerly a steam plant. Four underground diesel oil tanks are located along the east side of B443. Subsurface coring operations were conducted between the tanks by ER during August 2003 as part of the B443 Closure Investigation. At least 4 of the borings encountered Number 6 diesel oil (Bunker oil) in core and borehole materials. Liquid diesel oil was visible in some of the core and diesel stain occurred elsewhere. One of the cores contained oil to a depth of 21.5 feet below ground surface (Walsh and Stretesky, 2003). The water table was approximately 10 feet below surface during August 2003. There are few monitoring wells in the area and NAPL has not been observed.

# 4.2.5.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

No records or reports of any source area removal actions have been identified in PSA10.

#### 4.2.6 PSA12

PSA12 includes the CAH plume in the B-551/B-552 area.

#### 4.2.6.1 Description and Setting

The CAH plume of PSA12 apparently originates in the B-551/B-552 area and extends northeastwards towards B-559 and B-566.

#### 4.2.6.2 Local Hydrogeologic Influences and Variations

The groundwater flow direction in this area is to the north or northeast.

## 4.2.6.3 Historical Releases of Solvents and Fuels

No information on historical releases was found.

# 4.2.6.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

No information was found regarding source term removals in PSA12.

#### 4.2.7 PSA14

PSA14 includes IHSS 118.1 and is named Multiple Solvent Spills West of Building 730.

## 4.2.7.1 Description and Setting

IHSS 118.1 is located in the IA between B-730 and B-701. IHSS 118.1 is located south of B-771 and north of B-776. Various fuel oil tanks and process waste tanks (T-9 and T-10) are located near this IHSS. Subsurface investigations have been hindered by overhead and underground utilities and nearby underground process waste tanks.

### 4.2.7.2 Local Hydrogeologic Influences and Variations

Locally, groundwater flows to the north around B-771. Flow is locally influenced by the building drain system of B-771 which diverts groundwater from south to north around the building. This is an area crowded with buildings, pavement, and storage tanks.

#### 4.2.7.3 Historical Releases of Solvents and Fuels

The main source area for PSA14 is an underground storage tank that contained CT (RMRS, 1997). This tank was installed in about 1963, removed in 1981, and replaced by an above-ground tank. Numerous spills of CT occurred before 1970, some up to about 200 gallons (RMRS, 1997). During the late-1970's, the nearly full tank was thought to be empty and was refilled, spilling up to 1,000 gallons of CT. The CT flowed along the street south of B-701, then flowed north along the west side of B-701. During a later event of unknown date, the tank was again overfilled and 200 to 300 gallons of CT spilled from a vent pipe to the ground. The intake to the tank failed in June 1981 and released an unknown volume of CT into the containment structure. Subsurface investigations have found CT DNAPL as a free phase liquid in a bedrock low located beneath the former subsurface tank.

Although no reports of fuel releases have been found, No. 2 diesel fuel was detected in TPH analyses of NAPL samples from PSA14 during 1997 (RMRS, 1997, p.16-17). Up to 3,200 mg/L of TPH was found as a possible NAPL floating on groundwater in one or more wells. PSA14 wells known or suspected to have contained CT DNAPLs include 05197, 05397, 05497, 05897, 05997, and 18599.

# 4.2.7.4 Previous Work – Source Area Characterization, Interim Remedial Actions and Natural Attenuation Evaluations

During the OU9 Phase I RI in 1995, soil borings were made and subsurface soil and groundwater were sampled and analyzed. High concentrations of VOCs were detected in soils, notably borehole 02695



(between 22.0 and 22.8 ft) contained CT at 81,000 mg/kg and CF at 3,800 mg/kg; borehole 02895 (between 22.0 and 22.5 ft) contained CT at 25,000 mg/kg, however, CF was not detected; borehole 02995 (between 26.0 and 27.8 ft) contained CT at 9,800 mg/kg, however, CF was not detected (RMRS, 1997). Artificial fill material contained wood and trash in some of the borings.

Groundwater samples were collected by Hydropunch at locations adjacent to the soil borings during the 1995 work. Groundwater from boring 2795 separated into two liquid phases, and subsequent chemical analysis confirmed the presence of a CT DNAPL. The 1995 groundwater analysis from borehole 2795 detected CT at  $1,500 \mu g/L$  and CF at  $450 \mu g/L$ ; MC was not detected. Acetone was also detected at 110  $\mu g/L$  and PCE at  $14 \mu g/L$  in boring 2795. Groundwater sampled and analyzed in 1995 from boring 2695 contained CT at  $2,000 \mu g/L$ , CF at  $1,200 \mu g/L$ , and MC at  $22 \mu g/L$  (RMRS, 1997).

A pre-remedial field investigation took place during September 1997. Eight Geoprobe holes were planned to determine the extent of the DNAPL in subsurface soils contaminated by CT spills in IHSS 118.1 (RMRS, 1997). If potentially recoverable NAPL had been encountered, additional holes were to be pushed on 20 foot spacing to define the contamination. The presence of overhead and underground utilities forced relocation of 7 of the planned borings. The borehole materials were artificial fill and clay, gravely to sandy clay, and iron-stained sand alluvium. Asphalt fragments were observed in three of the borings. The bedrock contact was difficult to determine because of reworked bedrock claystone in the fill material. The borings found groundwater at 6.5 to 8.5 feet, while depth to bedrock was typically 14 to 24 feet below ground surface (RMRS, 1997).

During the 1997 work, DNAPL apparently pooled on the claystone bedrock surface in borehole 05397 at a depth of 21.5 ft. Boring 05997 encountered DNAPL just above bedrock at a depth of 24 feet. A well installed at boring 05497 was screened at the 17 to 22 foot depth interval; groundwater samples yielded DNAPL. An LNAPL slick was also observed during groundwater sampling at boring 05497. Boring 05897 encountered NAPL at a depth below 20 feet and bedrock at 21.4 feet (RMRS, 1997).

Primary contaminants encountered in borehole materials during the 1997 work included CT, CF, and MC. The latter compounds are degradation products of CT. However, both CF and MC were known to have been used in B-776 (RMRS, 1997).

NAPL samples collected during the 1997 investigation were a "dark brown color which is not associated with carbon tetrachloride" (RMRS, 1997). Analyses indicate that the NAPL samples were primarily CT, CF, and MC, with generally smaller concentrations of No. 2 diesel fuel up to 3,200 mg/L. Because No. 2 diesel fuel is light brown, the dark brown color of the NAPLs may be from pavement asphalt dissolved by the CT spills, weathering of the No. 2 diesel, and/or dissolution of a bituminous anti-corrosion coating from nearby tanks (RMRS, 1997).

A pit was excavated about 24 feet below ground surface during installation of the T-9 and T-10 process waste tanks in 1955. The underground CT tank was installed in 1963 at the western edge of the original excavation. This excavation is believed to be a closed depression in Arapahoe Formation claystone. The DNAPL is assumed to be the result of spills and leaks from the CT tank installed in 1963. The DNAPL is found on the bedrock surface of the closed depression in a layer about one-foot thick (RMRS, 1997). The DNAPL may fill the bottom of the excavation and extend under tanks T-9 and T-10. Low permeability claystone is believed to prevent downward migration of the CT and the closed basin prevents migration along the bedrock surface or nearby utility corridors. The water table is about 6 to 9 feet below ground surface. The total volume of DNAPL present in the excavation has been estimated at 2,000 to 2,900 gallons (RMRS, 1997).



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#### 5 DATA INTERPRETATIONS – NATURAL ATTENUATION AT RFETS

This chapter presents data interpretation and evidence of the extent of natural attenuation occurring in groundwater environment at the RFETS. Published literature suggests that at many chlorinated solvent sites, biodegradation is the most important attenuation process removing CAHs from groundwater. Therefore, this chapter emphasizes chemical evidence of biodegradation at the RFETS.

# 5.1 SITE-WIDE EVIDENCE OF NATURAL ATTENUATION

This section examines natural attenuation at the RFETS from a site-wide perspective and subsequently looks at the natural attenuation evidence pertaining to each of the 7 PSAs of special interest.

## 5.1.1 Biodegradation Screening

Wiedemeier scores were used to assess the evidence of biodegradation in individual monitoring wells (Wiedemeier et al., 1997; EPA, 1998). The score (explained in Section 3.1.2.1) is based on the concept that biodegradation will cause predictable changes in groundwater chemistry (EPA, 1998). If most of the relevant water quality parameters have been measured, then their concentrations may be scored by assigning points to each parameter. The points for all parameters are summed to produce a Wiedemeier score for each well. A total of 579 wells were scored using the Wiedemeier criteria. Because a range of point values for each well, minimum, mean, and maximum scores were computed. Only the maximum scores are discussed.

Wiedemeier scores for 579 monitoring wells at the RFETS ranged from a minimum of -3 points to a maximum of +22 points, with a mean and standard deviation of 3±3.4 points. The mean plus two standard deviations (M2SD) was 9.82. About 99.2% of wells at the RFETS have groundwater scores below 15 points indicating limited to no evidence of biodegradation. About 78% of wells have Wiedemeier scores below 6 points, indicating inadequate to no evidence for biodegradation. Figure 5-1 shows the spatial distribution of Wiedemeier scores across the IA and East Trenches areas.

Based on presently available data, well 33502 is the only well at the RFETS with that shows strong evidence of biodegradation. Well 33502 had a maximum score of 22. This well is located in PSA13 which is relatively small and is not discussed in detail in this report. Well 33502 is located under Sage Avenue, just north of B335.

Groundwater from well 33502 has elevated VC concentrations, ranging up to 1,200 µg/L in February 2003. Potential indicators of biodegradation at well 33502 include elevated mean concentrations of ferrous iron (22 mg/L) and total iron (30 mg/L), low ORP of -154 mV at field pH 6.95, and detectable



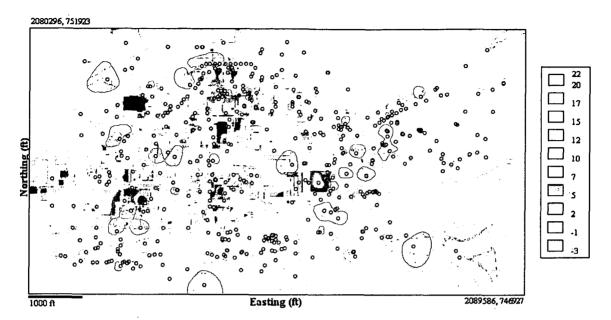


Figure 5-1 Isopleth Map of Wiedemeier Scores

sulfide (20  $\mu$ g/L). DO concentrations in groundwater at well 33502 are relatively low for the RFETS, averaging 1.6 mg/L.

Only one other well, well 1986, had adequate evidence of biodegradation with a maximum score of 19. Well 1986 is located in PSA14 about 1500 feet northeast of well 33502. Well 1986 is discussed further in Section 4.2.7.

All other wells had scores of 14 points or below as indicated below:

- 125 wells fell in the limited evidence of biodegradation category (6 to 14 points);
- 349 wells had inadequate evidence of biodegradation (1 to 5 points); and
- Hundreds of other wells and drains showed no positive evidence of biodegradation.

# 5.1.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Concentration versus time rate constants ( $K_p$ ), also called point attenuation rate constants, describe the attenuation of a CAH plume at a single monitoring well. As described in Section 3.1.3.3, these rate constants are based on the slope of a plot of ln C-vs-T.



To estimate  $K_p$  values, 282 plots of ln C-vs-T were constructed and the slope calculated. Declining or attenuating contaminant concentrations through time are indicated by negative slopes when regression lines are fitted to the plots. Most of the plots (168) exhibited negative slopes, while 114 of the plots had regression lines with positive slopes, indicating that CAH concentrations were not attenuating. All of these plots are shown in Appendix A. The  $K_p$  calculations are presented in Appendix B.

#### **5.1.2.1** Positive Point Attenuation Rate Constants

Recall that plots of negative slope (declining concentrations) yield positive  $K_p$  values. In other words, a positive  $K_p$  value indicates that natural attenuation is occurring. An example of an ln C-vs-T with a negative slope is shown on Figure 5-2. This chart shows that concentrations of PCE and its daughters, TCE and cis-1,2-DCE, are slowly decreasing with time. The decreasing concentrations of these chemicals are indicated by the negative slopes of the fitted regression lines. These slopes are used to compute  $K_p$  values. One hundred sixty-eight (168) of the RFETS wells had positive  $K_p$  values. These  $K_p$  values are listed in Table 5-1. Table 5-1 also shows the corresponding half-life for these  $K_p$  values.

-0.0002x<sub>3</sub>+ 4.6191 Natural Log of Concentration in ug/L -PCE €—TCE cis-1.2-DCE Linear (PCE) Linear (TCE) y = -0.0001x + 3.5132y = -0.0002x + 2.78041.5 Reference date 12/20/91 500 1000 1500 2000 2500 3000 3500 4000 4500 Elapsed Days Since Reference Date

Figure 5-2 Ln C vs Time Plot for PSA2A Well 00491 PCE Decay Series



K<sub>p</sub> values are contaminant- and well-specific. They can be used to estimate the time required for a plume of one contaminant to attenuate and eventually meet an attenuation goal (e.g., Tier II). Spatial assessment of CAH degradation across a groundwater plume requires adequate well coverage and monitoring of those wells over a long period of time. The RFETS has a long history of monitoring back to 1986, however, the monitoring wells are not always ideally located for a natural attenuation analysis.

Published literature at industrial sites suggests that the rate of weathering and attenuation of the DNAPLs sources are slower than the rate of attenuation of the CAHs dissolved in groundwater. In this case, the lifecycle of the groundwater plume is controlled by the rate of source attenuation and can be predicted by  $K_p$  rates measured for the most contaminated wells (Newell et al., 2002). Plumes meeting these criteria have concentration profiles that slowly retreat back towards the source area over time.

Actually, because degradation rates vary between wells, the well with the maximum observed concentration in groundwater may not require the longest attenuation time. Therefore, rate data should also be examined for wells with the second or third highest contaminant concentrations. Because different chemicals degrade at different rates in the same well, it is also valuable to report the analyte and well with the longest predicted time to achieve an attenuation goal (e.g., Tier II) by natural attenuation. Table 5-1 shows the date that natural attenuation is predicted to achieve Tier II.

Each row of Table 5-1 contains a  $K_p$  value and corresponding half-life for a specific CAH and well. If the concentration of the chemical in the well at time zero is less than the Tier II action level, then the right-hand column says "Never Exceeded." This means that the chemical has not exceeded Tier II during the period for which we have monitoring data and its concentration should continue to naturally attenuate in the future. If the chemical concentration at time zero exceeded the Tier II goal, then the  $K_p$  rate is used to predict the date when the contaminant is expected to naturally attenuate to meet Tier II.

Table 5-1 Positive Point Attenuation Rate Constants for Wells Located in CAH Plumes

PS.	A Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (µg/L)	K <sub>p</sub> (per year)	Half-Life (years)	Predicted Date To Meet Goal If Decay Continues
2	00491	1,1-DCA	3650	12/20/91	-0.00001	0.3	0.0037	189.8	Never Exceeded
2	00491	1,1-DCE	7	12/20/91	-0.00010	0.5	0.0365	19.0	Never Exceeded
2	00491	CF	100	12/20/91	-0.00020	91.9	0.0731	9.5	Oct 1990
2	00491	cis-1,2-DCE	70	12/20/91	-0.00020	16.1	0.0731	9.5	Nov 1971
2	00491	СТ	5	12/20/91	-0.00030	240.1	0.1096	6.3	Apr 2027
2	00491	PCE	5	12/20/91	-0.00010	33.6	0.0365	19.0	Feb 2044



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (μg/L)	K <sub>p</sub> (per year)	Half-Life (years)	Predicted Date To Meet Goal If Decay Continues
2	00491	TCE	5	12/20/91	-0.00020	101.4	0.0731	9.5	Mar 2033
2	01291	CF	100	5/21/92	-0.00003	23.4	0.0110	63.3	Never Exceeded
2	06591	CF	100	5/19/92	-0.00050	62.3	0.1826	3.8	Oct 1989
2	06591	СТ	5	5/19/92	-0.00020	154.0	0.0731	9.5	Apr 2039
2	06691	1,1,1-TCA	200	5/19/92	-0.00070	76.9	0.2557	2.7	Aug 1988
2	06691	1,1-DCA	3650	5/19/92	-0.00110	66.9	0.4018	1.7	Jun 1982
2	06691	1,1-DCE	7	5/19/92	-0.00050	23.9	0.1826	3.8	Feb 1999
2	06691	CF	100	5/19/92	-0.00040	21750.7	0.1461	4.7	Mar 2029
2	06691	МС	5	5/19/92	-0.00110	13911.9	0.4018	1.7	Feb 2012
2	06691	TCE	5	5/19/92	-0.00008	141.1	0.0292	23.7	Sep 2106
2	06991	1,1-DCE	7	5/18/92	-0.00010	0.8	0.0365	19.0	Never Exceeded
2	06991	СТ	5	5/18/92	-0.00010	21.0	0.0365	19.0	Aug 2031
2	0987	MC	5	10/12/87	-0.00060	11.6	0.2192	3.2	Aug 1991
2	13191	1,1,1-TCA	200	5/19/92	-0.00050	14.1	0.1826	3.8	Nov 1977
2	13191	1,1-DCA	3650	5/19/92	-0.00040	4.6	0.1461	4.7	Never Exceeded
2	13191	CF	100	5/19/92	-0.00090	565.3	0.3287	2.1	Aug 1997
2	13191	MC	5	5/19/92	-0.00090	106.6	0.3287	2.1	Sep 2001
2	13191	PCE	5	5/19/92	-0.00010	68.7	0.0365	19.0	Feb 2064
2	1587	1,1,1-TCA	200	9/10/87	-0.00010	3.4	0.0365	19.0	Never Exceeded
2	1587	1,1-DCE	7	9/10/87	-0.00004	5.6	0.0146	47.4	May 1972
2	1587	CF	100	9/10/87	-0.00020	41.7	0.0731	9.5	Sep 1975
2	1587	СТ	5	9/10/87	-0.00020	2926.0	0.0731	9.5	Dec 2074
2	1587	PCE	5	9/10/87	-0.00030	369.3	0.1096	6.3	Dec 2026
2	1587	TCE	5	9/10/87	-0.00030	187.8	0.1096	6.3	Oct 2020
2	90299	TCE	5	8/5/99	-0.00050	3.7	0.1826	3.8	Nov 1997
3	0271	1,1-DCE	7	8/27/86	-0.00120	37.8	0.4383	1.6	Jul 1990
3	0271	CF	100	8/27/86	-0.00030	171.0	0.1096	6.3	Jul 1991
3	0271	PCE	5	8/27/86	-0.00040	91.5	0.1461	4.7	Jul 2006
3	0271	TCE	5	8/27/86	-0.00060	10356.8	0.2192	3.2	Jun 2021
3	06791	CF	100	5/20/92	-0.00140	0.8	0.5114	1.4	Jan 1983
3	06791	СТ	5	5/20/92	-0.00010	5.8	0.0365	19.0	Jun 1996

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PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (μg/L)	K <sub>p</sub> (per year)	Half-Life (years)	Predicted Date To Meet Goal If Decay Continues
3	06791	PCE	. 5	5/20/92	-0.00160	0.7	0.5844	1.2	Jan 1989
3	07391	1,1,1-TCA	200	3/16/92	-0.00030	465.4	0.1096	6.3	Nov 1999
3	07391	1,1-DCA	3650	3/16/92	-0.00060	340.7	0.2192	3.2	May 1981
3	07391	1,1-DCE	7	3/16/92	-0.00020	235.9	0.0731	9.5	May 2040
3	07391	CF	100	3/16/92	-0.00009	1719.9	0.0329	21.1	Sep 2078
3	07391	cis-1,2-DCE	70	3/16/92	-0.00050	357.7	0.1826	3.8	Feb 2001
3	07391	СТ	5	3/16/92	-0.00100	1742.0	0.3653	1.9	Mar 2008
3	07391	TCE	5	3/16/92	-0.00009	73939.3	0.0329	21.1	Apr 2284
3	1187	1,1,1-TCA	200	9/16/87	-0.00040	7.7	0.1461	4.7	May 1965
3	1187	1,1-DCE	7	9/16/87	-0.00020	7.5	0.0731	9.5	Sep 1988
3	1187	CF	100	9/16/87	-0.00007	97.0	0.0256	27.1	Jul 1986
3	1187	cis-1,2-DCE	70	9/16/87	-0.00010	13.4	0.0365	19.0	Never Exceeded
3	1187	СТ	5	9/16/87	-0.00030	713.4	0.1096	6.3	Dec 2032
3	1187	PCE	5	9/16/87	-0.00003	37.7	0.0110	63.3	Jan 2172
5	00897	CF	100	9/30/97	-0.00001	3.0	0.0037	189.8	Never Exceeded
5	00897	MC	5	9/30/97	-0.00170	9296.6	0.6209	1.1	Nov 2009
5	0174	TCE	5	8/26/86	-0.00010	2924.3	0.0365	19.0	Feb 2161
5	01791	MC	5	12/19/91	-0.00320	14.1	1.1688	0.6	Nov 1992
5	01791	PCE	5	12/19/91	-0.00020	10.2	0.0731	9.5	Sep 2001
5	02291	1,1,1-TCA	200	12/16/91	-0.00040	10.1	0.1461	4.7	Jul 1971
5	02291	1,1-DCA	3650	12/16/91	-0.00020	2.9	0.0731	9.5	Never Exceeded
5	02291	1,1-DCE	7	12/16/91	-0.00020	8.9	0.0731	9.5	Mar 1995
5	02291	CF	100	12/16/91	-0.00008	3.9	0.0292	23.7	Never Exceeded
5	02291	СТ	5	12/16/91	-0.00009	0.6	0.0329	21.1	Never Exceeded
5	12091	MC	5	12/19/91	-0.00410	16.7	1.4975	0.5	Oct 1992
5	15699	1,1,1-TCA	200	3/10/99	-0.00060	22.0	0.2192	3.2	Feb 1989
5	15699	1,1-DCE	7	3/10/99	-0.00010	63.6	0.0365	19.0	Aug 2059
5	15699	CF	100	3/10/99	-0.00100	24.2	0.3653	1.9	Apr 1995
5	15699	cis-1,2-DCE	70	3/10/99	-0.00120	323.4	0.4383	1.6	Sep 2002
5	15699	PCE	5	3/10/99	-0.00150	912.0	0.5479	1.3	Sep 2008
5	15699	TCE	5	3/10/99	-0.00170	1819.7	0.6209	1.1	Sep 2008



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (μg/L)	K <sub>p</sub> (per year)	Half-Life (years)	Predicted Date To Meet Goal If Decay Continues
5	1987	PCE	5	5/22/90	-0.00040	1048.6	0.1461	4.7	Dec 2026
5	1987	TCE	5	5/22/90	-0.00040	80.2	0.1461	4.7	May 2009
5	2387	MC	5	9/10/87	-0.00070	5.5	0.2557	2.7	Feb 1988
5	4386	СТ	5	3/11/87	-0.00005	2.7	0.0183	38.0	Mar 1953
7	02091	CF	100	12/14/91	-0.00100	0.4	0.3653	1.9	Jan 1977
7	02091	СТ	5	12/14/91	-0.00060	0.6	0.2192	3.2	Dec 1981
7	03391	1,1,1-TCA	200	12/5/91	-0.00050	4.5	0.1826	3.8	Mar 1971
7	03391	1,1-DCE	7	12/5/91	-0.00030	4.0	0.1096	6.3	Dec 1986
7	03391	CF	100	12/5/91	-0.00010	15.5	0.0365	19.0	Never Exceeded
7	03391	TCE	5	12/5/91	-0.00010	69.3	0.0365	19.0	Nov 2063
7	03691	1,1,1-TCA	200	6/8/92	-0.00030	6.3	0.1096	6.3	Nov 1960
7	03691	1,1-DCE	7	6/8/92	-0.00040	5.3	0.1461	4.7	Jul 1990
7	03691	CF	100	6/8/92	-0.00020	28.5	0.0731	9.5	Apr 1975
7	03691	cis-1,2-DCE	70	6/8/92	-0.00003	10.6	0.0110	63.3	Never Exceeded
7	- 03691	СТ	5	6/8/92	-0.00020	364.5	0.0731	9.5	Feb 2051
7	03691	TCE	5	6/8/92	-0.00020	55.5	0.0731	9.5	May 2025
7	0374	1,1,1-TCA	200	8/25/86	-0.00130	27.8	0.4748	1.5	Jun 1982
7	0374	1,1-DCE	7	8/25/86	-0.00080	11.4	0.2922	2.4	Apr 1988
7	0374	CF	100	8/25/86	-0.00030	21.0	0.1096	6.3	Jun 1972
7	0374	СТ	5	8/25/86	-0.00060	907.5	0.2192	3.2	May 2010
7	0374	PCE	5	8/25/86	-0.00100	360.2	0.3653	1.9	May 1998
7	0374	TCE	5	8/25/86	-0.00100	230.9	0.3653	1.9	Feb 1997
7	11891	1,1,1-TCA	200	12/19/91	-0.00020	3.5	0.0731	9.5	Never Exceeded
7	11891 -	1,1-DCE	7	12/19/91	-0.00010	3.2	0.0365	19.0	Dec 1970
7	11891	CF	100	12/19/91	-0.00004	14.6	0.0146	47.4	Never Exceeded
7	11891	TCE	5	12/19/91	-0.00020	64.9	0.0731	9.5	Jan 2027
7	12191	1,1,1-TCA	200	3/16/92	-0.00050	7.5	0.1826	3.8	Mar 1974
7	12191	1,1-DCE	7	3/16/92	-0.00020	5.1	0.0731	9.5	Dec 1987
7	12191	CF	100	3/16/92	-0.00010	7.9	0.0365	19.0	Never Exceeded
7	12191	СТ	5	3/16/92	-0.00004	195.3	0.0146	47.4	Jan 2243
7	12191	TCE	5	3/16/92	-0.00006	40.9	0.0219	31.6	Feb 2088



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	$T_0$ Concentration ( $\mu g/L$ )	K <sub>p</sub> (per year)	HalfLife (years)	Predicted Date To Meet Goal If Decay Continues
7	2487	PCE	5	6/7/90	-0.00010	2.8	0.0365	19.0	Mar 1974
7	2587	CF	100	9/10/87	-0.00010	3.8	0.0365	19.0	Never Exceeded
7	2587	СТ	5	9/10/87	-0.00004	91.3	0.0146	47.4	Jun 2186
7	2587	МС	5	9/10/87	-0.00020	10.6	0.0731	9.5	Dec 1997
7	2587	PCE	5	9/10/87	-0.00020	344.1	0.0731	9.5	Aug 2045
7	2587	TCE	5	9/10/87	-0.00030	86.1	0.1096	6.3	Sep 2013
10	40499	1,1-DCA	3650	11/9/99	-0.00230	0.3	0.8401	0.8	Sep 1988
10	40499	cis-1,2-DCE	70	11/9/99	-0.00130	8.1	0.4748	1.5	Apr 1995
10	40499	PCE	5	11/9/99	-0.00120	11.7	0.4383	1.6	Oct 2001
10	40499	TCE	5	11/9/99	-0.00120	2.7	0.4383	1.6	Jun 1998
10	41299	1,1-DCA	3650	11/9/99	-0.00130	3.2	0.4748	1.5	Jan 1985
10	41299	1,1-DCE	7	11/9/99	-0.00120	15.9	0.4383	1.6	Sep 2001
10	41299	cis-1,2-DCE	70	11/9/99	-0.00110	73.0	0.4018	1.7	Dec 1999
10	41299	PCE	5	11/9/99	-0.00070	365.5	0.2557	2.7	Aug 2016
10	41299	TCE	5	11/9/99	-0.00080	56.2	0.2922	2.4	Feb 2008
10	P416889	1,1,1-TCA	200	11/23/93	-0.00050	0.9	0.1826	3.8	Mar 1964
10	P416889	1,1-DCA	3650	11/23/93	-0.00020	1.1	0.0731	9.5	Never Exceeded
10	P416889	1,1-DCE	7	11/23/93	-0.00030	4.2	0.1096	6.3	Mar 1989
10	P416889	cis-1,2-DCE	70	11/23/93	-0.00030	8.4	0.1096	6.3	Jul 1974
10	P416889	PCE	5	11/23/93	-0.00003	44.8	0.0110	63.3	Dec 2193
10	P416889	TCE	5	11/23/93	-0.000005	3.3	0.0018	379.5	Never Exceeded
10	P419689	1,1,1-TCA	200	11/19/93	-0.00080	0.8	0.2922	2.4	Nov 1974
10	P419689	1,1-DCA	3650	11/19/93	-0.00040	5.0	0.1461	4.7	Never Exceeded
10	P419689	1,1-DCE	7	11/19/93	-0.00040	2.7	0.1461	4.7	May 1987
10	P419689	CF	100	11/19/93	-0.00003	0.8	0.0110	63.3	Never Exceeded
10	P419689	cis-1,2-DCE	70	11/19/93	-0.00009	8.2	0.0329	21.1	Never Exceeded
10	P419689	PCE	5	11/19/93	-0.00010	25.2	0.0365	19.0	Mar 2038
10	P419689	TCE	5	11/19/93	-0.00020	2.8	0.0731	9.5	Jan 1986
12	1986	1,1-DCA	3650	9/18/86	-0.00050	3.7	0.1826	3.8	Never Exceeded
12	1986	cis-1,2-DCE	70	9/18/86	-0.00060	2.8	0.2192	3.2	Dec 1971
12	. 1986	МС	5	9/18/86	-0.00060	8.6	0.2192	3.2	Mar 1989



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (μg/L)	K <sub>p</sub> (per year)	Half-Life (years)	Predicted Date To Meet Goal If Decay Continues
12	1986	trans-1,2- DCE	70	9/18/86	-0.00100	5.1	0.3653	1.9	Jul 1979
12	21298	CF	100	9/22/98	-0.00004	7.0	0.0146	47.4	Never Exceeded
12	21298	СТ	5	9/22/98	-0.00003	11.1	0.0110	63.3	Jul 2071
12	21598	TCE	5	9/23/98	-0.00010	85.3	0.0365	19.0	May 2076
12	21798	1,1-DCA	3650	9/15/98	-0.00050	7.4	0.1826	3.8	Sep 1964
12	21798	cis-1,2-DCE	70	9/15/98	-0.00008	11.9	0.0292	23.7	Never Exceeded
12	21898	1,1-DCA	3650	9/22/98	-0.00020	1.0	0.0731	9.5	Never Exceeded
12	84702	1,1,1-TCA	200	4/9/02	-0.00380	19.9	1.3880	0.5	Aug 2000
12	84702	1,1-DCA	3650	4/9/02	-0.00190	66.1	0.6940	1.0	Jun 1996
12	84702	1,1-DCE	7	4/9/02	-0.00370	115.6	1.3514	0.5	May 2004
12	84702	CF .	100	4/9/02	-0.00110	0.7	0.4018	1.7	Nov 1989
12	84702	chloroethane	29.4	4/9/02	-0.00270	5.8	0.9862	0.7	Aug 2000
12	84702	cis-1,2-DCE	70	4/9/02	-0.00250	12.1	0.9131	0.8	May 2000
12	84702	PCE	5	4/9/02	-0.00370	418.3	1.3514	0.5	Jul 2005
12	84702	TCE	5	4/9/02	-0.00330	95.0	1.2053.	0.6	Sep 2004 .
12	P114789	CF	100	11/22/93	-0.00030	0.6	0.1096	6.3	Never Exceeded
12	P114789	cis-1,2-DCE	70	11/22/93	-0.00030	9.5	0.1096	6.3	Aug 1975
12	P114789	МС	5	11/22/93	-0.00030	0.9	0.1096	6.3	Jun 1978
12	P114789	TCE	5	11/22/93	-0.00040	4.3	0.1461	4.7	Nov 1992
14	18199	МС	5	3/17/99	-0.00220	626.7	0.8036	0.9	Mar 2005
14	18199	TCE	5	3/17/99	-0.00007	3.7	0.0256	27.1	Oct 1987
_14_	18499	MC	5	_3/17/99_	0.00110_	435.6	0.4018	1.7	Apr 2010
14	18499	PCE	5	3/17/99	-0.00020	117.0	0.0731	9.5	May 2042
14	18599	CF	100	3/2/99	-0.00130	2658.5	0.4748	1.5	Jan 2006
14	18599	СТ	5	3/2/99	-0.00070	14439.2	0.2557	2.7	May 2030
14	18699	1,1-DCA	3650	3/17/99	-0.00110	1.5	0.4018	1.7	Oct 1979
14	18799	1,1-DCA	3650	3/17/99	-0.00110	3.3	0.4018	1.7	Oct 1981
14	18799	CF	100	3/17/99	-0.00001	529.1	0.0037	189.8	May 2455
14	18799	мс	5	3/17/99	-0.00210	27.7	0.7670	0.9	Jun 2001
14	20998	CF	100	9/22/98	-0.00020	81.2	0.0731	9.5	Nov 1995



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	$\Gamma_0$ Concentration ( $\mu g/L$ )	K <sub>p</sub> (per year)	Half-Life (years)	Predicted Date To Meet Goal If Decay Continues
14	20998	MC	5	9/22/98	-0.00230	14.4	0.8401	0.8	Dec 1999
14	21002	ст	5	11/11/02	-0.00340	2982.7	1.2419	0.6	Jan 2008
14	21002	PCE	5	11/11/02	-0.00010	2.6	0.0365	19.0	Sep 1984
14	21098	CF	100	9/22/98	-0.00060	439.8	0.2192	3.2	Jun 2005
14	22696	CF	100	2/4/97	-0.00020	1.0	0.0731	9.5	Never Exceeded
14	771FD OUT#2	PCE	5	3/26/99	-0.00070	10.8	0.2557	2.7	Mar 2002
14	77492	cis-1,2-DCE	70	3/22/93	-0.00010	0.6	0.0365	19.0	Never Exceeded

If all of the half-lives for positive  $K_p$  values are grouped by chemical some interesting statistics emerge. Table 5-2 arranges the CAH parents and daughters in order of their average point attenuation half-lives in the RFETS groundwater. There is only one rate measurement for chloroethane (CA), but at 0.7 years, it has the shortest half-life of the CAHs investigated. The published literature indicates that CA has a hydrolysis half-life of 0.12 years, so the agreement between the Site and literature values is reasonable.

Table 5-2 Point Attenuation Half-lives of CAH Compounds in Groundwater

САН	Minimum Half-Life (years)	Mean Half- Life (years)	Maximum Half-Life (years)	Standard Deviation (years)	Number of Measurements
CA	0.70	0.70	0.70	0.0	1
trans-1,2-DCE	1.90	1.90	1.90	0.0	1
мс	0.46	2.51	9.5	2.5	14
1,1,1-TCA	0.50	5.07	19.0	4.4	15
1,1-DCE	0.51	10.74	47.4	11.2	18
cis-1,2-DCE	0.76	12.90	63.3	16.6	14
PCE	0.51	13.88	63.3	18.3	20
1,1-DCA	0.83	16.46	189.8	48.0	15
ст	0.56	18.10	63.3	19.2	17
TCE	0.58	26.72	379.5	77.4	23
CF	1.36	28.22	189.8	48.1	29

Of the parent solvents, 1,1,1-TCA is expected to have a relatively short half-life because its hydrolysis half-life is 0.5 to 2.5 years. In the RFETS groundwater, the mean half-life of 1,1,1-TCA is comparable at



5 years. TCE, CT, and PCE are the longest lived parent CAHs with a half-lives of 27, 18, and 14 years, respectively. CF is the first daughter of CT and has the longest mean half-life, 28 years, of any CAH in the RFETS groundwater. MC, the second daughter of CT, is readily attenuated and has a short half-life of 2.5 years.

### **5.1.2.2** Negative Point Attenuation Rate Constants

Not all of the calculated  $K_p$  values were positive. One hundred fourteen (114) of the ln C-vs-T plots exhibited positive regression slopes indicating that chemical concentrations were actually increasing through time at selected wells. The corresponding  $K_p$  values and half-lives are negative indicating that concentrations are increasing faster than natural attenuation processes can lower them. Therefore, net attenuation is not occurring. An example of an ln C-vs-T plot with a positive slope (i.e., negative  $K_p$ ) is shown on Figure 5-3.

Table 5-3 lists 114 negative K<sub>p</sub> values and corresponding half-lives. This table is similar to Table 5-1 except the concentrations are increasing. Therefore, if the time zero concentration was below Tier II, the right-hand column predicts the date when the CAH might exceed Tier II. On the other hand, if the contaminant concentration at time zero was greater than Tier II, then the CAH concentration is predicted to continue to increase and the right-hand column says "Always Exceeded."

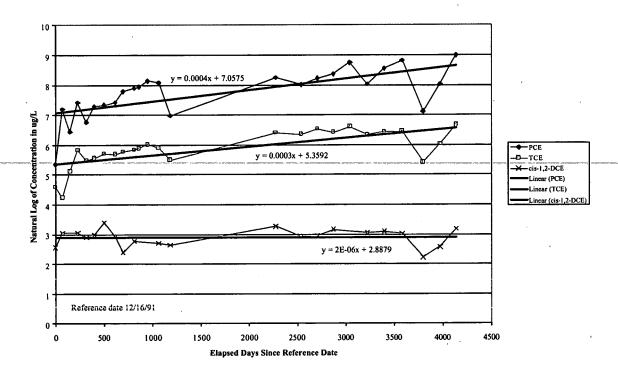


Figure 5-3 Ln C vs Time Plot for PSA5A Well 02291 PCE Decay Series



Table 5-3. Negative Point Attenuation Rate Constants for Wells Located in CAH Plumes

PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (µg/L)	Κ <sub>ρ</sub> (per year)	Half-life (years)	Predicted Date To Exceed Goal If Concentrations Continue To Increase
2	01291	СТ	5	5/21/92	0.00002	9.7	-0.0073	-94.9	Always Exceeded
2	01291	PCE	5	5/21/92	0.0002	1.0	-0.0731	-9.5	Dec 2013
2	01291	TCE	5	5/21/92	0.0003	6.2	-0.1096	-6.3	May 1990
2	06591	1,1-DCA	3650	5/19/92	0.0035	0.7	-1.2784	-0.5	Jan 1999
2	06691	Chloromethane	6.55	5/19/92	0.0079	44.4	-2.8855	-0.2	Sep 1991
2	06691	cis-1,2-DCE	70	5/19/92	0.000004	3.0	-0.0015	-474.4	Jun 4145
2	06691	СТ	5	5/19/92	0.0006	23458.8	-0.2192	-3.2	Oct 1953
2	06991	cis-1,2-DCE	70	5/18/92	0.0004	17.9	-0.1461	-4.7	Sep 2001
2	06991	PCE	5	5/18/92	0.0004	95.2	-0.1461	-4.7	Mar 1972
2	06991	TCE	5	5/18/92	0.0004	4.0	-0.1461	-4.7	Nov 1993
2	13191	1,1-DCE	7	5/19/92	0.00006	16.5	-0.0219	-31.6	Mar 1953
2	13191	cis-1,2-DCE	70	5/19/92	0.0004	2.2	-0.1461	-4.7	Feb 2016
2	13191	CT	5	5/19/92	0.0004	1320.4	-0.1461	-4.7	Mar 1954
2	13191	TCE	5	5/19/92	0.0001	6.8	-0.0365	-19.0	Nov 1983
2	90299	CF	100	8/5/99	0.0003	2.6	-0.1096	-6.3	Dec 2032
2	90299	СТ	5	8/5/99	0.0002	1.0	-0.0731	-9.5	May 2021
3	0271	1,1,1-TCA	200	8/27/86	0.0003	10.8	-0.1096	-6.3	Apr 2013
3	0271	1,1-DCA	3650	8/27/86	0.0008	5.6	-0.2922	-2.4	Nov 2008
3	0271	MC	5	8/27/86	0.0008	2.3	-0.2922	-2.4	Apr 1989
3	0271	trans-1,2-DCE	70	8/27/86	0.0008	26.6	-0.2922	-2.4	Dec 1989
3	07391	MC	5	3/16/92	0.0014	97.6	-0.5114	-1.4	May 1986
3	07391	PCE	5	3/16/92	0.000003	1025.6	-0.0011	-632.5	Always Exceeded
3	1187	TCE	5	9/16/87	0.0002	1334.6	-0.0731	-9.5	Always Exceeded
5	00897	cis-1,2-DCE	70	9/30/97	0.0003	36.8	-0.1096	-6.3	Aug 2003
5_	00897	PCE	5	9/30/97	0.0003	10748.3	-0.1096	-6.3	Always Exceeded
5	00897	TCE	5	9/30/97	0.00002	1371.1	-0.0073	-94.9	Always Exceeded
5	0174	PCE	5	8/26/86	0.0003	20355.4	-0.1096	-6.3	Always Exceeded
5	01791	TCE	5	12/19/91	0.0001	0.3	-0.0365	-19.0	Nov 2073
5	02291	cis-1,2-DCE	70	12/16/91	0.000002	18.0	-0.0007	-948.8	Jul 3854
5	02291	MC	5	12/16/91	0.0002	28.6	-0.0731	-9.5	Jan 1968
5	02291	PCE	5	12/16/91	0.0004	1161.5	-0.1461	-4.7	Aug 1954
5	02291	TCE	5	12/16/91	0.0003	212.6	-0.1096	-6.3	Sep 1957
5	12091	PCE	5	12/19/91	0.00001	0.3	-0.0037	-189.8	Oct 2743
5	15699	1,1-DCA	3650	3/10/99	0.00005	19.5	-0.0183	-38.0	Oct 2285
5	15699	MC	5	3/10/99	0.0061	25.1	-2.2280	-0.3	Jun 1998



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (µg/L)	K <sub>p</sub> (per year)	Half-life (years)	Predicted Date To Exceed Goal If Concentrations Continue To Increase
5	75992	MC	5	8/17/94	0.0041	0.0	-1.4975	-0.5	Dec 1997
7	02091	cis -1,2-DCE	70	12/14/91	0.000007	84.4	-0.0026	-271.1	Always Exceeded
7	02091	MC	5	12/14/91	0.0129	0.0	-4.7117	-0.1	Dec 1993
7	02091	PCE	5	12/14/91	0.0003	2552.9	-0.1096	-6.3	Always Exceeded
7	02091	TCE	5	12/14/91	0.00006	163.8	-0.0219	-31.6	Always Exceeded
7	03391	cis-1,2-DCE	70	12/5/91	0.00006	17.5	-0.0219	-31.6	Mar 2055
7	03391	СТ	5	12/5/91	0.0001	302.8	-0.0365	-19.0	Always Exceeded
7	03391	PCE	5	12/5/91	0.0001	190.8	-0.0365	-19.0	Always Exceeded
7	03691	MC	5	6/8/92	0.0028	0.2	-1.0227	-0.7	May 1995
7	03691	PCE	5	6/8/92	0.00006	212.9	-0.0219	-31.6	Always Exceeded
7	0374	MC	5	8/25/86	0.00001	4.1	-0.0037	-189.8	Apr 2044
7	11891	1,1-DCA	3650	12/19/91	0.00006	0.3	-0.0219	-31.6	Nov 2425
7	11891	cis-1,2-DCE	70	12/19/91	0.00006	14.7	-0.0219	-31.6	Apr 2063
7	11891	СТ	5	12/19/91	0.00009	314.3	-0.0329	-21.1	Always Exceeded
7	11891	MC	5	12/19/91	0.0004	3.8	-0.1461	-4.7	Oct 1993
7	11891	PCE	5	12/19/91	0.00007	166.1	-0.0256	-27.1	Always Exceeded
7	12191	cis-1,2-DCE	70	3/16/92	0.00009	9.5	-0.0329	-21.1	Jan 2053
7	12191	MC	5	3/16/92	0.0001	25.0	-0.0365	-19.0	Always Exceeded
7	12191	PCE	5	3/16/92	0.0001	202.9	-0.0365	-19.0	Always Exceeded
7	24193	1,1,1-TCA	200	10/22/93	0.0016	47.7	-0.5844	-1.2	Apr 1996
~~7 ~	24193	1,1-DCE	7	-10/22/93-	0.0008	27.7	0.2922	-2.4	Feb 1989
7	24193	CF	100	10/22/93	0.0015	79.5	-0.5479	-1.3	Mar 1994
7	24193	СТ	5	10/22/93	0.0015	1060.4	-0.5479	-1.3	Jan 1984
7	24193	PCE	5	10/22/93	0.0018	914.3	-0.6575	-1.1	Nov 1985
7	24193	TCE	5	10/22/93	0.0014	64.2	-0.5114	-1.4	Oct 1988
7	24393	1,1,1-TCA	200	10/26/93	0.0058	6.4	-2.1185	-0.3	Jun 1995
7	24393	1,1-DCE	7	10/26/93	0.0058	4.0	-2.1185	-0.3	Jan 1994
7	24393	CF	100	10/26/93	0.0061	9.0	-2.2280	-0.3	Nov 1994
7	24393	cis-1,2-DCE	70	10/26/93	0.0005	8.0	-0.1826	-3.8	Sep 2005
7	24393	CT	5	10/26/93	0.0051	223.9	-1.8628	-0.4	Oct 1991
7	24393	PCE	5	10/26/93	0.0033	224.0	-1.2053	-0.6	Aug 1990
7	24393	TCE	5	10/26/93	0.0013	40.1	-0.4748	-1.5	Jun 1989
7	2487	СТ	5	6/7/90	0.00003	0.9	-0.0110	-63.3	Jun 2151



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (µg/L)	K <sub>p</sub> (per year)	Half-life (years)	Predicted Date To Exceed Goal If Concentrations Continue To Increase
7	2587	cis-1,2-DCE	70	9/10/87	0.0005	1.7	-0.1826	-3.8	Dec 2007
10	10498	cis-1,2-DCE	70	8/12/98	0.0006	0.1	-0.2192	-3.2	Sep 2026
10	10498	MC	5	8/12/98	0.0029	0.5	-1.0592	-0.7	Oct 2000
10	10498	PCE	5	8/12/98	0.0005	28.0	-0.1826	-3.8	Mar 1989
10	10498	TCE	5	8/12/98	0.0042	0.0	-1.5341	-0.5	Aug 2001
10	40199	CF	100	9/1/99	0.0019	0.1	-0.6940	-1.0	Sep 2009
10	40199	PCE	5	9/1/99	0.0023	0.5	-0.8401	-0.8	May 2002
10	41299	CF	100	11/9/99	0.0009	1.2	-0.3287	-2.1	Apr 2013
10	P416889	MC	5	11/23/93	0.0007	0.7	-0.2557	-2.7	Jun 2001
12	1986	TCE	5	9/18/86	0.0003	6.8	-0.1096	-6.3	Dec 1983
12	21498	cis-1,2-DCE	70	9/22/98	0.0011	0.6	-0.4018	-1.7	Jul 2010
12	21498	TCE	5	9/22/98	0.0006	1.9	-0.2192	-3.2	Feb 2003
12	21598	1,1-DCA	3650	9/23/98	0.00003	1.9	-0.0110	-63.3	Jan 2690
12	21598	1,1-DCE	7	9/23/98	0.0003	2.8	-0.1096	-6.3	Feb 2007
12	21598	cis-1,2-DCE	70	9/23/98	0.00009	8.1	-0.0329	-21.1	Jun 2064
12	21598	PCE	5	9/23/98	0.0001	12.0	-0.0365	-19.0	Sep 1974
12	21598	vinyl chloride	2	9/23/98	0.0013	0.4	-0.4748	-1.5	Dec 2001
12	21898	cis-1,2-DCE	70	9/22/98	0.00006	4.5	-0.0219	-31.6	Mar 2124
14	00600	1,1-DCA	3650	6/6/01	0.0015	0.5	-0.5479	-1.3	Oct 2017
14	00600	1,1-DCE	7	6/6/01	0.0007	0.8	-0.2557	-2.7	Dec 2009
14	18199	CF	100	3/17/99	0.0004	2818.6	-0.1461	<b>-4</b> .7·	May 1976
14	18199	CT	5	3/17/99	0.0005	15717.0	-0.1826	-3.8	Feb 1955
14	18199	PCE	5	3/17/99	0.0002	49.8	-0.0731	-9.5	Sep 1967
14	18299	CF	100	3/17/99	0.0013	1547.8	-0.4748	-1.5	Jun 1993
14	18299	PCE	5	3/17/99	0.0009	25.5	-0.3287	-2.1	Apr 1994
14	18499	CF	100	3/17/99	0.00005	5151.8	-0.0183	-38.0	Always Exceeded
14	18499	chloromethane	6.55	3/17/99	0.0016	9.4	-0.5844	-1.2	Aug 1998
14	18499	СТ	5	3/17/99	0.0003	19002.0	-0.1096	-6.3	Always Exceeded
14	18599	MC	5	3/2/99	0.0016	129.3	-0.5844	-1.2	Aug 1993
14	18799	1,1-DCE	7	3/17/99	0.0001	7.1	-0.0365	-19.0	Nov 1998
14	18799	СТ	5	3/17/99	0.0003	504.7	-0.1096	-6.3	Feb 1957
· 14	18799	PCE	5	3/17/99	0.0006	7.0	-0.2192	-3.2	Sep 1997
14	18799	TCE	5	3/17/99	0.001	0.2	-0.3653	-1.9	Jun 2007
14	20898	CF	100	9/21/98	0.0004	66.0	-0.1461	-4.7	Jul 2001
14	20898	cis-1,2-DCE	70	9/21/98	0.0006	0.7	-0.2192	-3.2	Aug 2019
14	20898	СТ	5	9/21/98	0.0003	58.1	-0.1096	-6.3	May 1976
14	20898	PCE	5	9/21/98	0.0002	2.8	-0.0731	-9.5	Aug 2006
14	20998	СТ	5	9/22/98	0.0016	45.3	-0.5844	-1.2	Dec 1994
14	20998	PCE	5	9/22/98	0.0005	0.3	-0.1826	-3.8	Oct 2014
14	21002	CF	100	11/11/02	0.0008	194.3	-0.2922	-2.4	Aug 2000



PSA	Well	САН	Tier II Goal (µg/L)	Reference Date of Plot	Ln C vs T Slope (per day)	T <sub>0</sub> Concentration (µg/L)	K <sub>b</sub> (per year)	Half-life (years)	Predicted Date To Exceed Goal If Concentrations Continue To Increase
14	21002	MC	5	11/11/02	0.0024	1.1	-0.8766	-0.8	Aug 2004
14	771FD OUT#2	1,1-DCE	7	3/26/99	0.0009	1.1	-0.3287	-2.1	Nov 2004
14	771FD OUT#2	CF	100	3/26/99	0.001	30.3	-0.3653	-1.9	Jul 2002
14	771FD OUT#2	СТ	5	3/26/99	0.0018	20.6	-0.6575	-1.1	Jan 1997
14	77492	СТ	5	3/22/93	0.0009	2.8	-0.3287	-2.1	Jan 1995
14	77492	MC	5	3/22/93	0.0027	0.6	-0.9862	-0.7	May 1995

The conceptual model suggests that locally increasing concentrations of daughter products will occur at some of the wells (also see Appendix I). Therefore, negative point attenuation rate constants are understandable for daughter products. However, Table 5-3 also shows numerous parent solvents (CT, PCE, 1,1,1-TCA, and some TCE) whose concentrations increase through time. Increasing parent concentrations may suggest that a contaminant source continues to release contaminants to groundwater. Further discussion of the negative Kp values is provided in Section 5.1.3.2.

# 5.1.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Approximately 170 plots were prepared showing ln C-vs-D for wells located along a contaminant flowpath (Appendix C). Each plot shows the trend in detected concentrations of a single CAH at multiple wells located along the flowpath during a selected time window. These plots were prepared to determine bulk attenuation rate constants (K<sub>b</sub>) for individual CAHs in each of the 7 PSAs during time intervals with sufficient data. If three or more data points were available (i.e., the mean concentrations at three or more wells) and were reasonably linear on the plot, then a regression line was fitted. The K<sub>b</sub> value equals the negative slope of the line times the contaminant velocity in appropriate units. The method of computing bulk attenuation rate constants was described in Section-3.1.2.4. The K<sub>b</sub> calculations are presented in Appendix D.

Because ln C-vs-D plots and  $K_b$  values represent a narrow time window, they are not useful for estimating plume longevity (Newell et al., 2002). However, they are useful to predict the future plume extent, or size of a plume, and whether it should grow, shrink, or remain at steady-state. They can also be used to estimate biodegradation rate constants for steady-state plumes.



### 5.1.3.1 Positive Bulk Attenuation Rate Constants

From a Site-wide perspective, 103 of the plots had regression lines with negative slopes and positive  $K_b$  values indicating that the CAH concentrations are naturally attenuating within certain plumes. Calculated  $K_b$  values and their corresponding half-lives are listed in Table 5-4. An example of an ln C-vs-D plot with a negative slope is shown on Figure 5-4. This figure shows that cis-1,2-DCE concentrations are steadily attenuating as groundwater migrates along flowpath A in PSA7 during 2002-2003.

Table 5-4 Positive Bulk Attenuation Rate Constants

PSA	Time Period	САН	La C~s-D Stope (per ft)	Bulk Attenuation Rate K (per year)	Bulk Attenuation Half-Life (years)	Tier II Goal (μg/L)	Max imum Concentration (µg/L) at Well Near Source During Time Period	COC Velocity (fl/yr)	Decay Time (years) To Meet Tier II Goal	Predicted Decay Length (ft) From Well With Maximum Source	Estimated Existing Plume Length (ft) From Well With Max imum Source	Is the Plume Predicted to Grow or Shrink After Time Period?
2	2002 - 2003	1,1-DCE	-0.0026	0.083	8.3	7	34.1	32.0	19.0	609	175	Grow
2	2002 - 2003	CF	-0.0010	0.047	14.9	100	10500	46.6	99.9	4654	514	Grow
2	2002 - 2003	cis-1,2- DCE	-0.0009	0.034	20.3	70	59.6	37.9	-4.7	0	665	Shrink
2	2002 - 2003	СТ	-0.0020	0.044	15.8	5	9960	21.9	173.6	3798	2035	Grow
2	2002 - 2003	PCE	-0.0017	0.022	31.6	5	545	12.9	213.8	2760	1075	Grow
2	2000- 2001	МС	-0.0060	0.232	3.0	5	9.8	38.6	2.9	112	223	Shrink
2	1998- 1999	1,1-DCA	-0.0001	0.004	162.7	3650	1	42.6	-1925.2	0	0	Steady
2	1998- 1999	1,1-DCE	-0.0009	0.029	24.1	7	5	32.0	-11.7	0	634	Shrink
2	1998- 1999	CF	-0.0007	0.033	21.3	100	2750	46.6	101.7	4735	484	Grow
2	1998- 1999	СТ	-0.0033	0.072	9.6	5	43550	21.9	125.6	2749	1834	Grow
2	1998- 1999	МС	-0.0030	0.116	6.0	5	14510	38.6	68.9	2658	1311	Grow
2	1998- 1999	PCE	-0.0033	0.043	16.3	5	4980	12.9	162.1	2092	1734	Steady
2	1998- 1999	TCE	-0.0005	0.013	53.2	5	180	26.1	274.9	7167	1834	Grow
2	1994- 1995	1,1,1 <i>-</i> TCA	-0.0018	0.026	26.7	200	13.9	14.4	-102.6	0	0	Steady
2	1994- 1995	1,1-DCE	-0.0043	0.138	5.0	7	168.4	32.0	23.1	740	15	Grow
2	1994- 1995	CF	-0.0013	0.061	11.4	100	13967	46.6	81.6	3799	234	Grow
2	1994- 1995	СТ	-0.0017	0.037	18.6	5	63667	21.9	254.1	5560	1434	Grow
2	1994- 1995	МС	-0.0040	0.154	4.5	5	4300	38.6	43.8	1689	259	Grow
2	1994- 1995	PCE	-0.0007	0.009	76.7	5	129	12.9	359.7	4643	1075	Grow
2	1994- 1995	TCE	-0.0005	0.013	53.2	5	472	26.1	348.9	9095	1585	Grow



PSA	Time Period	САН	Ln C-vs-D Slope (per ft)	Bulk Attenuation Rate K (per year)	Bulk Attenuation Half-Life (years)	Tier II Goal (μg/L)	Max imum Concentration (µg/L) at Well Near Source During Time Period	COC Velocity (ft/yr)	Decay Time (years) To Meet Tier II Goal	Predicted Decay Length (ft) From Well With Maximum Source	Estimated Existing Plume Length (ft) From Well With Max imum Source	Is the Plume Predicted to Grow or Shrink After Time Period?
2	1992- 1993	1,1,1-TCA	-0.0015	0.022	32.0	200	63.8	14.4	-52.7	0	0	Steady
2	1992 - 1993	1,1-DCA	-0.0021	0.089	7.7	3650	84.5	42.6	-42.1	0	0	Steady
2	1992 - 1993	1,1-DŒ	-0.0015	0.048	14.4	7	25.3	32.0	26.8	857	234	Grow
2	1992 - 1993	CF	-0.0006	0.028	24.8	100	25035	46.6	197.6	9205	1311	Grow
2	1992- 1993	cr	-0.0015	0.033	21.1	5	28646.5	21.9	263.6	5769	1634	Grow
2	1992 - 1993	мс	-0.0004	0.015	44.9	5	13554	38.6	512.2	19762	1634	Grow
2	1992 - 1993	PCE	-0.0007	0.009	76.7	5	636.9	12.9	536.4	6925	1584	Grow
3	2002 - 2003	.TCE	-0.0190	0.495	1.4	5	33625	26.1	17.8	464	497	Steady
3	2000- 2001	мс	-0.0140	0.540	1.3	5	2481	38.6	11.5	443	677	Shrink
3	1992 - 1993	1,1,1-TCA	-0.0172	0.248	2.8	200	488.1	14.4	3.6	52	77	Shrink
3	1992 - 1993	1,1-DŒ	-0.0124	0.397	1.7	7	196.4	32.0	8.4	269	97	Grow
5	2002 - 2003	CF	-0.0043	1.505	0.5	100	2.9	349.9	-2.4	0	0	Steady
5	2002 - 2003	cis-1,2- DCE	-0.0060	1.710	0.4	70	71.5	285.0	0.0	4	15	Shrink
5	2002 - 2003	мс	-0.0094	2.725	0.3	5	1120	289.9	2.0	576	195	Grow
5	2002 - 2003	TCE	-0.0017	0.333	2.1	5	1201	195.9	16.5	3224	425	Grow
5	2000 - 2001	МС	-0.0100	2.899	0.2	5	1410	289.9	1.9	564	375	Grow
5	2000- 2001	PCE	-0.0123	1.193	0.6	5	18600	97.0	6.9	668	525	Grow
5	2000- 2001	TCE	-0.0100	1.959	0.4	5	1600	195.9	2.9	577	875	Shrink
5	1998- 1999	МС	-0.0063	1.826	0.4	5	5067	289.9	3.8	1099	925	Steady
5	1998- 1999	PCE	-0.0075	0.727	1.0	5	11470	97.0	10.6	1032	525	Grow
5	1992- 1993	CF	-0.0105	3.674	0.2	100	350	349.9	0.3	119	147	Steady
5	1990- 1991	мс	-0.0001	0.029	23.9	5	2060	289.9	207.7	60210	1197	Grow
5	1986- 1987	TCE	-0.0015	0.294	2,4	5	6142	195.9	24.2	4742	1197	Grow -
7	2002 - 2003	1,1-DCE	-0.0018	0.405	1.7	7	2.2	225.0	-2.9	0	0	Steady
7	2002 - 2003	cis-1,2- DCE	-0.0016	0.427	1.6	70	64.9	266.7	-0.2	0	0	Steady
7	2002 - 2003	PCE	-0.0023	0.209	3.3	5	3970	90.7	32.0	2903	1550	Grow
7	2002 - 2003	TCE	-0.0025	0.458	1.5	5	156	183.3	7.5	1376	1500	Steady
7	1996- 1997	1,1,1-TCA	-0.0003	0.030	22.8	200	4.4	101.5	-125.3	0	0	Steady



PSA	Time Period	САН	Ln C~s-D Slope (per ft)	Bulk Attenuation Rate K (per year)	Bulk Attenuation Half-Life (years)	Tier II Goal (μg/L)	Max imum Concentration (µg/L) at Well Near Source During Time Period	COC Velocity (ft/yr)	Decay Time (years) To Meet Tier II Goal	Predicted Decay Length (ft) From Well With Maximum Source	Estimated Existing Plume Length (ft) From Well With Max imum Source	Is the Plume Predicted to . Grow or Shrink After Time Period?
7	1996- 1997	1,1-DCE	-0.0009	0.202	3,4	7	4.4	225.0	-2.3	0.	0	Steady
7	1996- 1997	ст	-0.0026	0.400	1.7	5	483.3	153.8	11.4	1758	361	Grow
7	1994 <i>-</i> 1995	1,1,1-TCA	-0.0058	0.589	1.2	200	123.5	101.5	-0.8	0	0	Steady
7	1994- 1995	1,1-DŒ	-0.0010	0.225	3.1	7	52	225.0	8.9	2005	13	Grow
7	1994- 1995	CF	-0.0017	0.557	1,2	100	210	327.4	1.3	436	8	Grow
7	1994- 1995	cis-1,2- DCE	-0.0017	0.453	1,5	70	116.6	266.7	1.1	300	150	Grow
7	1994- 1995	СТ	-0.0022	0.338	2.0	5	3300	153.8	19.2	2951	723	Grow
7	1994- 1995	МС	-0.0024	0.651	1.1	5	58.5	271.3	3.8	1025	1050	Steady
7	1994- 1995	PCE	-0.0022	0.200	3.5	5	6460	90.7	35.9	3256	1300	Grow
7	1994- 1995	TCE	-0.0004	0.073	9.5	5	210	183.3	51.0	9344	1290	Grow
7	1992- 1993	cis-1,2- DCE	-0.0019	0.507	1.4	70	106.5	266.7	0.8	221	170	Grow
7	1992- 1993	PCE	-0.0011	0.100	6.9	5	4608	90.7	68.4	6206	1200	Grow
7	1992- 1993	TCE	-0.0013	0.238	2.9	5	200.3	183.3	15.5	2839	1100	Grow
7	1990- 1991	1,1,1-TCA	-0.0029	0.294	2.4	200	40	101.5	-5.5	0	0	Steady
7	1990- 1991	1,1-DCE	-0.0054	1.215	0.6	7	31	225.0	1.2	276	280	Steady
7	1990- 1991	cis-1,2- DCE	-0.0015	0.400	1,7	70	47	266.7	-1.0	0	0	Steady
7	1990- 1991	СТ	-0.0009	0.138	5.0	5	444	153.8	32.4	4985	217	Grow
7	1990- 1991	МС	-0.0008	0.217	3,2	5	7	271.3	1.6	421	458	Steady
7	1990- 1991	PCE	-0.0006	0.054	12.7	5	305.6	90.7	75.5	6855	558	Grow
7	1990 1991	TCE	-0.0003	0.055	12.6	5	94	183.3	53.4	9780	900	Grow
10	2002- 2003	cis-1,2- DCE	-0.0011	0.024	29.0	70	23.4	21.8	-45.8	0	0	Steady
10	2002 - 2003	PCE	-0.0004	0.003	234.0	5	179	7.4	1208.2	8945	576	Grow
10	2000- 2001	мс	-0.0015	0.033	20.9	5	22.3	22.1	45.0	997	890	Steady
10	2000- 2001	PCE	-0.0006	0.004	156.0	5	627.4	7.4	1087.8	8054	1450	Grow
10	1996- 1997	TCE	-0.0007	0.010	66.2	5	2.7	15.0	-58.9	0	0	Steady
12	2002- 2003	1,1-DCA	-0.0024	0.543	1.3	3650	53.4	226.3	-7.8	0	0	Steady
12	2002- 2003	1,1-DŒ	-0.0011	0.187	3.7	7	85.2	170.0	13.4	2272	552	Grow
12	2002- 2003	МС	-0.0002	0.041	16.9	5	0.7	205.0	-48.0	0	0	Steady



PSA	Time Period	САН	Ln C-vs-D Slope (per ft)	Bulk Attenuation Rate K (per year)	Bulk Attenuation Half-Life (years)	Tier II Goal (μg/L)	Max imum Concentration (µgL) at Well Near Source During Time Period	COC Velocity (ft/yr)	Decay Time (years) To Meet Tier II Goal	Predicted Decay Length (ft) From Well With Maximum Source	Estimated Existing Plume Length (ft) From Well With Max Imum Source	Is the Plume Predicted to Grow or Shrink After Time Period?
12	2002 - 2003	PCE	-0.0001	0.007	101.1	5	309.7	68.6	601.7	41262	1072	Grow
12	2002- 2003	VC	-0.0040	1.983	0.3	2	9	495.8	0.8	376	271	Grow
12	1998- 1999	1,1-DCA	-0.0032	0.724	1.0	3650	7	226.3	-8.6	0 .	0	Steady
12	1998- 1999	1,1-DŒ	-0.0002	0.034	20.4	7	2	170.0	-36.8	0	-1279	Grow
12	1998- 1999	cis-1,2- DCE	-0.0052	1.048	0.7	70	11.3	201.5	-1.7	0	0	Steady
12	1998- 1999	МС	-0.0019	0.389	1.8	5	21.1	205.0	3.7	758	67	Grow
12	1998- 1999	PCE	-0.0017	0.117	5.9	5	11.6	68.6	7.2	495	117	Grow
12	1998- 1999	TCE	-0.0011	0.152	4.5	5	83.4	138.5	18.5	2558	417	Grow
14	2002 - 2003 2002 -	CF	-0.0056	0.243	2.9	100	5665	43.4	16.6	721	473	Grow
14	2002 - 2003 2002 -	Сī	-0.0071	0.145	4.8	5	29700	20.4	60.1	1224	619	Grow
14	2003	МС	-0.0046	0.165	4.2	5 .	71.2	35.9	16.1	577	263	Grow
14	2002 - 2003 2002 -	PCE	-0.0062	0.075	9.3	5	96	12.0	39.6	477	373	Grow
14	2003	TCE	-0.0008	0.019	35.7	5	2.5	24.3	-35.7	0	0	Steady
14	2000- 2001	1,1-DCA	-0.0022	0.087	7.9	3650	1.1	39.7	-92.9	0	0	Steady
14	2000- 2001	CF	-0.0067	0.291	2.4	100	4696	43.4	13.2	575	583	Steady
14	2000- 2001	СТ	-0.0032	0.065	10.6	5	25423	20.4	130.9	2667	619	Grow
14	2000- 2001	мс	-0.0024	0.086	8.0	5	2038	35.9	69.7	2504	530	Grow
14	2000 - 2001	PCE	-0.0057	0.069	10.1	5	74.7	12.0	39.5	474	483	Steady
14	2000- 2001	TCE	-0.0022	0.053	13.0	5	6	24.3	3.4	83	69	Steady
14	1998- 1999	1,1-DCA	-0.0035	0.139	5.0	3650	2.4	<sup></sup> 39.7	-52.8	- 0	0	Steady
14	1998- 1999	1,1-DCE	-0.0029	0.086	8.0	7	7	29.8	0.0	0	0	Steady
14	1998- 1999	CF	-0.0037	0.160	4.3	100	2608	43.4	20.3	881	399	Grow
14	1998- 1999	cis-1,2- DCE	-0.0009	0.032	21.8	70	1.6	35.3	-118.8	0	0	Steady
14	1998- 1999	СТ	-0.0062	0.126	5.5	5	14073	20.4	62.9	1281	700	Grow
14	1998- 1999	мс	-0.0043	0.155	4.5	5	287.8	35.9	26.2	943	578	Grow
14	1998- 1999	PCE	-0.0072	0.087	8.0	5	150	12.0	39.3	472	253	Grow
14	1998- 1999	TCE	-0.0042	0.102	6.8	5	5.5	24.3	0.9	23	8	Grow



Data coverage and availability was generally adequate for  $K_b$  calculation. Except for chloromethane and chloroethane,  $K_b$  values were computed for all CAHs of interest during multiple time periods and in several different areas of the RFETS.

Table 5-4 indicates a wide range of predicted decay times for these CAHs to attenuate in concentration and reach Tier II. Positive decay durations range from one to more than 1,200 years to attenuate to Tier II. Negative decay times indicate that the maximum concentration of the CAH was less than Tier II along the flowpath during the selected time period.

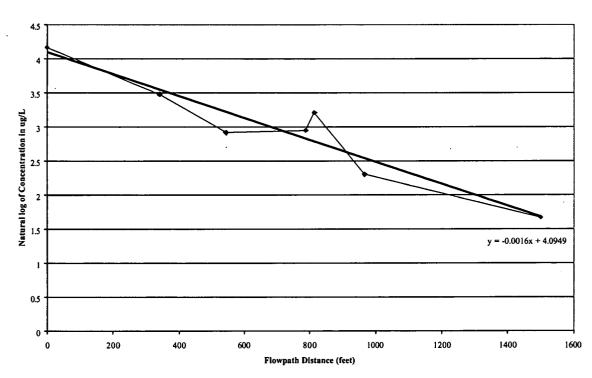


Figure 5-4 Ln C vs Distance Plot for cis-1,2-DCE Along Path PSA7A During 2002-2003

The calculated  $K_b$  values predict that most of the plumes will grow in the future. Sixty one of the  $K_b$  values suggest that the plumes will grow, while 35 of the  $K_b$  values suggest that the plumes are at steady-state. Only 7 of the  $K_b$  values suggest that the plumes will shrink. Note that these predictions are for the period following the end of the time period of calculation which is shown at the left side of Table 5-4. As expected, the plumes that are predicted to shrink are attenuating faster, i.e., they have an average bulk attenuation half-life of 7.5 years. In contrast, plumes predicted to grow are attenuating slower, with average bulk attenuation half-lives of 19.8 years. The half-life of steady-state plumes averaged 15.1 years.



The bulk attenuation rate data may be grouped in various ways to gain a Site-wide understanding of natural attenuation. Grouping the positive bulk attenuation rates by CAH indicates that K<sub>b</sub> values are available for 10 CAHs. Arranged from highest to lowest average attenuation rate (per year) these include VC (1.98), CF (0.66), MC (0.60), cis-1,2-DCE (0.51), TCE (0.28), 1,1-DCA (0.26), 1,1-DCE (0.25), 1,1,1-TCA (0.20), PCE (0.17), CT (0.14). VC has the highest average attenuation rate and is known to be the most volatile of the CAHs, having a Henry's Law constant of 1.22 atm-m³/mole. Volatilization alone does not, however, explain the attenuation ranking of these 10 compounds. For example, CT is the least attenuated but has the second highest Henry's constant of 0.03 atm-m³/mole, so it would be expected to follow VC if volatilization is the predominant attenuation mechanism. Similarly, CF, MC and cis-1,2-DCE have the lowest Henry's law constants (0.0043, 0.0027, 0.0037 atm-m³/mole, respectively), and therefore should have the lowest attenuation rates if volatilization dominated natural attenuation.

Another possibility is that the observed  $K_b$  order is a function of the reaction rates characteristic of each CAH, whether by abiotic hydrolysis, oxidation, or biodegradation. Half-lives have been published for many of these CAHs undergoing abiotic hydrolysis and dehydrohalogenation reactions (EPA, 1998). However, there seems to be no relationship between these abiotic chemical half-lives and the observed  $K_b$  order. Bulk attenuation rates reflect all natural attenuation processes at a site and are normally greater than the corresponding biodegradation rates. Published biodegradation rates are site-specific and vary over many orders of magnitude (EPA, 1998). Therefore, published biodegradation rates were not compared against the mean  $K_b$  rates of this evaluation.

The  $K_b$  ranking also does not appear to correlate with  $K_{oc}$  values for these CAHs. High  $K_{oc}$  values indicate strong sorption to the porous medium and strongly sorbed CAHs should produce a high  $K_b$  value. Compared with the attenuation ranking discussed above, the opposite is generally seen when the CAHs are ranked from lowest to highest minimum  $K_{oc}$  values (ml/g; EPA, 1998). The  $K_{oc}$  ranking includes VC (0.4), CF (<34), 1,1-DCA (40), MC (48), cis-1,2-DCE (49), 1,1-DCE (65), TCE (87), CT (110), 1,1,1-TCA (183), and PCE (209). The  $K_{oc}$  values increase from weakly sorbed VC to strongly sorbed PCE.

If biodegradation is the dominant attenuation mechanism and occurs most rapidly in solution and not on solid surfaces, then a larger fraction of the weakly sorbed CAHs might be more readily biodegraded. It's possible that this effect makes biodegradation of weakly sorbed CAHs more easily measured via concentration changes. As the dissolved fraction of a strongly sorbed chemical is biodegraded, the  $K_d$  concept requires that the dissolved fraction be replenished by desorption, thus maintaining the concentration in solution and yielding a lower bulk degradation rate.

Based on the above comparisons, no single attenuation mechanism appears to be dominant. Grouping the positive bulk attenuation rates by CAH and then by period, it was noted that the highest bulk attenuation rates occurred during different time periods for different chemicals. MC, cis-1,2-DCE, and 1,1-DCA exhibited their highest average K<sub>b</sub> rates (to date) during 2002-2003. PCE and TCE had their greatest mean attenuation rates during 2000-2001. The largest mean rate for CT was during 1996-1997. There

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does not seem to be a systematic pattern, as other chemicals had their highest mean rates during older periods. It is therefore concluded that the bulk attenuation rates reflect the composite effects of many of the natural attenuation processes.

#### 5.1.3.2 Negative Bulk Attenuation Rate Constants

Sixty-four (64) of the  $\ln$  C-vs-D plots (38%) had regression lines with positive slopes indicating that the concentrations of some CAHs were increasing downgradient along the flowpath. The  $K_b$  values and their corresponding half-lives calculated using these plots are listed in Table 5-5. The  $\ln$  C-vs-D plots are included in Appendix C.

The corresponding  $K_b$  values are negative because net attenuation is not occurring. Appendix I contains several figures which show how daughter products may accumulate and peak in concentration before eventually decaying away. An example of an ln C-vs-D plot with a positive slope is shown as Figure 5-5. This figure shows that the concentrations of CF are steadily increasing along flowpath A in PSA12 during 2002-2003.

2 1.5 y = 0.0023x - 2.3271 1 0.5 0 200 400 600 800 1000 1200 1400 1600 1800 2000

Figure 5-5 Ln C vs Distance Plot for Chloroform Along Path PSA7A During 2002-2003



Review Exemption: CEX-105-01

Flowpath Distance (feet)

Table 5-5 Negative Bulk Attenuation Rate Constants

PSA	Time Period	САН	Ln C-vs-D Slope (per ft)	Bulk Attenuation Rate (per year)
2	2002-2003	TCE	0.00001	-0.0003
2	2002-2003	1,1-DCA	0.0009	-0.038
2	1998-1999	cis-1,2-DCE	0.0009	-0.034
2	1994-1995	cis-1,2-DCE	0.0009	-0.034
2	1992-1993	cis-1,2-DCE	0.0011	-0.042
2	1992-1993	TCE	0.0006	-0.016
2	1990-1991	MC	0.0010	-0.039
-3	1994-1995	CF	0.0103	-0.480
3	1994-1995	PCE	0.0112	-0.145
3	1994-1995	TCE	0.0171	-0.446
3	1992-1993	CF	0.0106	-0.494
3	1992-1993	CT	0.0113	-0.247
3	1992-1993	PCE	0.0072	-0.093
3	1992-1993	TCE	0.0100	-0.261
3	1990-1991	MC	0.0030	-0.116
5	2000-2001	CF	0.0048	-1.680
5	2000-2001	cis-1,2-DCE	0.0007	-0.200
5	1998-1999	1,1-DCE	0.0136	-3.270
5	1998-1999	CF	0.0057	-1.995
5	1998-1999	cis-1,2-DCE	0.0057	-1.625
5	1998-1999	CT	0.0106	-1.743
5	1998-1999	trans-1,2-DCE	0.0034	-1.154
5	1994-1995	PCE	0.0161	-1.561
5	1994-1995	TCE	0.0168	-3.290
5	1992-1993	MC	0.0009	-0.261
5	1992-1993	PCE	0.0182	-1.765
5	/ 1992-1993	TCE	0.0143	-2.801
5	1990-1991	PCE	0.0152	-1.474
5 .	1990-1991	TCE	0.0107	-2.096
7	2002-2003	CF	0.0007	-0.229
7	2002-2003	CT	0.0043	-0.662



PSA	Time Period	САН	Ln C-vs-D Slope (per ft)	Bulk Attenuation Rate (per year)
7	1996-1997	CF	0.0019	-0.622
7	1996-1997	cis-1,2-DCE	0.0009	-0.240
7	1996-1997	TCE	0.0002	-0.037
7	1992-1993	1,1,1-TCA	0.0020	-0.203
7	1992-1993	1,1-DCE	0.0005	-0.112
7	1992-1993	CF	0.0038	-1.244
7	1992-1993	CT	0.0064	-0.985
7	1992-1993	MC	0.0015	-0.407
7	1992-1993	trans-1,2-DCE	0.0017	-0.540
7	1990-1991	CF	0.0036	-1.179
10	2002-2003	CF	0.0018	-0.048
10	2002-2003	TCE	0.0008	-0.012
10	2000-2001	CF	0.0040	-0.107
10	2000-2001	cis-1,2-DCE	0.0029	-0.063
10	2000-2001	CT	0.0030	-0.038
10	2000-2001	TCE	0.0010	-0.015
10	1998-1999	1,1,1-TCA	0.0013	-0.011
10	1998-1999	1,1-DCA	0.0024	-0.059
10	1998-1999	CF	0.0015	-0.040
10	1998-1999	cis-1,2-DCE	0.0028	-0.061
10	1998-1999	MC	0.0008	-0.018
10	1998-1999	PCE	0.0014	-0.010
10	1998-1999	TCE	0.0027	-0.040
10	1992-1993	PCE	0.0039	-0.029
12	2002-2003	CF	0.0023	-0.569
12	2002-2003	cis-1,2-DCE	0.0012	-0.242
12	2002-2003	TCE	0.0001	-0.014
12	1998-1999	CF	0.0082	-2.029
12	1998-1999	CT	0.0039	-0.453
14	2002-2003	1,1-DCE	0.0003	-0.009
14	2000-2001	1,1-DCE	0.0016	-0.048
14	2000-2001	cis-1,2-DCE	0.0032	-0.113
14	1998-1999	chloromethane	0.0031	-0.136



Table 5-5 shows that each of the PSAs investigated have between 4 and 14 negative  $K_b$  values. Therefore, the increasing concentration trends are areally distributed across the Site and are not localized.

Forty of the 64 negative  $K_b$  values (Table 5-5) occur in CAH plumes exceeding Tier II which may increase in concentration before attenuating. The remaining plumes with 24 negative  $K_b$  values have concentrations less than Tier II may exceed Tier II in the future. However, a few short-term predictions of future exceedances of Tier II using the negative  $K_b$  values have not proved to be accurate. For example, PSA5 during 1998-1999 (Table 5-5) shows that CF at 25  $\mu$ g/L is predicted to reach Tier II (100  $\mu$ g/L) in about 1 year. Although CF does continue to have a negative  $K_b$  in PSA5 during 2000-2001, its concentration has actually decreased to 16  $\mu$ g/L in well 15699 which continues to exhibit the highest CF concentrations along the flowpath.

Policy decisions affected the groundwater monitoring performed during various periods of the RFETS' history. Nevertheless, two time periods have the most frequent occurrences of negative  $K_b$  values. These include 1992-1993 and 1998-1999. The reason for these frequent occurrences is not known.

As expected, VC does not have any negative  $K_b$  values. VC should be rapidly oxidized by the elevated DO concentrations observed in most areas of the RFETS. VC is also the most likely CAH to be lost through volatilization.

The most frequent compounds with negative  $K_b$  rates are CF and TCE, followed by cis-1,2-DCE. Although CT was heavily used at the RFETS, only 6 negative  $K_b$  values were calculated CT. Including its daughters, the CT decay series accounts for 24 of the 64 negative  $K_b$  values. The PCE-TCE decay series accounts for 31 of the 64 negative  $K_b$  rates.

CAH concentrations may increase downgradient through several possible mechanisms. For example, the general conceptual model (Figure 3-5b) shows that daughter products are expected to increase in concentration along some segments of the plume flowpath before peaking and then attenuating (see also Appendix I). This is a likely explanation if the ln C-vs-D plots with positive slopes happen to span the portion of the plume with increasing concentrations of daughter products. If more complete monitoring data existed along the central flowpaths of CAH plumes at the RFETS, we would expect to see the complete cycle of increasing, peaking, and attenuating daughter products.

Daughter product concentrations should increase whenever they are being produced more rapidly than they sorb to the porous medium or decay. Appendix I indicates that daughter concentrations should increase to a peak and then decrease, regardless of the relative decay rates of the parent and daughter compound.

Another potential explanation for increasing CAH concentrations downgradient might be loss of water through net evapotranspiration. This argument would require that the concentrations of the less volatile



CAHs increase (along with those of most inorganic ions) as water molecules were removed. The extent of volatilization of a CAH depends on its vapor pressure and Henry's Law constant. Henry's Law states that the chemical concentration in the air equals the aqueous concentration times the Henry's Law constant. This means that the more volatile compounds have larger Henry's Law constants. The CAH most likely to be lost from groundwater through volatilization is VC which has a large Henry's Law constant of 1.22 atm-m³/mole. By contrast, CT has a Henry's Law constant of only 0.030 atm-m³/mole which indicates that it is not significantly volatile. Other CAHs have even smaller Henry's Law constants, as low as 0.003 atm-m³/mole for MC (EPA, 1998), and are essentially nonvolatile.

However, virtually all CAHs have Henry's Law constants greater than  $10^{-7}$  atm-m³/mole and are more volatile than water (Howard, 1989). Therefore, CAHs are more likely to volatilize during net evaporation of groundwater than accumulate in groundwater. During transpiration, plant roots would be expected to remove dissolved CAHs from the UHSU. However, inspection of numerous plots of inorganic constituents (e.g., nitrate, sulfate, chloride) do not show consistent increases indicative of water loss. Small increases in chloride concentration may be the natural result of dechlorination reactions (i.e., of biodegradation and hydrolysis). The trends are complicated by the potential reduction of some nitrate and sulfate. These lines of evidence suggest that net evapotranspiration does not account for increasing downgradient CAH concentrations.

A hypothetical explanation for increasing CAH concentrations downgradient is that sorbed CAHs may be desorbed from the porous medium because of changes in groundwater quality. This could result from a change in pH or an ion exchange mechanism where a more strongly sorbed constituent may bind to the sorption sites, displacing the CAH and resulting in a net increase in CAH concentration downgradient..

There is some evidence in the literature that supports this hypothesis.  $K_d$  values of chlorinated solvents are commonly estimated from the TOC content of the porous medium. Naturally occurring organic matter in sediments often has a high cation exchange capacity (CEC), the magnitude of which varies strongly with pH (Drever, 1988, p.92). Similarly, the magnitude of  $K_d$  values are often pH dependent and may be a function of other ions in groundwater (Langmuir, 1997; Drever, 1988).

In summary, 62% of the ln C-vs-D plots had negative slopes and positive  $K_b$  values indicating that natural attenuation processes are lowering the CAH concentrations in groundwater at the RFETS. However, 38% of the ln C-vs-D plots indicated that CAHs were locally increasing in concentration faster than they are naturally attenuated. The most likely explanation for the increasing concentrations is that plume segments with positive slopes show only the rising limb of increasing daughter product concentrations. If additional monitoring wells were available along the full length of the CAH plume flowpaths, then the daughter concentrations should peak and then decrease with distance as indicated in the conceptual model Figure 3-5.

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## 5.1.4 Biodegradation Rate Constants

Biodegradation rate constants were computed by the 1D method of Buscheck and Alcantar (1995). The Buscheck and Alcantar method was described in Section 3.1.3.5. Key input data to the method include the slopes of the ln C-vs-D plots and the longitudinal dispersivity. Longitudinal dispersivity was estimated as 10% of the average plume length (Fetter, 1988). The plume length was defined as the length extending from the maximum contaminant concentration to the farthest downgradient Tier II boundary. This resulted in a Site-wide longitudinal dispersivity of about 53 feet. The 1D method also requires that the plume be at steady-state during the time period, otherwise the computed rate constant will be an approximation of the true biodegradation rate. The biodegradation rate constants were calculated along the A flowpaths in each PSA. The resulting calculations are provided in Appendix D.

Thirty-five biodegradation rate constants were computed for individual CAH plumes which are predicted to be at steady-state based on bulk attenuation rates (Table 5-6). These rates may be thought of as the fraction of the aqueous concentration of a CAH that is biodegraded per year. Therefore, it does not matter if the concentration units are  $\mu g/L$ , mg/L, or some other concentration unit. Multiplying the fractional rate by 100% expresses the rate as a percentage per year (e.g., 0.768 is equal to 76.8%).

Table 5-6 Biodegradation Rate Constants for CAH Plumes at Steady-State

PSA	Time Period	САН	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
7	1994-1995	1,1,1-TCA	0.768	0.9
7	1990-1991	1,1,1-TCA	0.339	2.0
7	1996-1997	1,1,1-TCA	0.031	. 22.4
2	1994-1995	1,1,1-TCA	0.028	24.4
2	1992-1993	1,1,1-TCA	0.023	29.7
12	1998-1999	1,1-DCA	0.846	0.8
12	2002-2003	1,1-DCA	0.612	1. 100 same g
14	1998-1999	1,1-DCA	0.164	4.2
2	1992-1993	1,1-DCA	0.099	7.0
14	2000-2001	1,1-DCA	0.097	7.1
2	1998-1999	1,1-DCA	0.004	161.8
7	1990-1991	1,1-DCE	1.560	0.4
7	2002-2003	1,1-DCE	0.443	1.6
7	1996-1997	1,1-DCE	0.212	3.3
14	1998-1999	1,1-DCE	0.100	7.0



PSA	Time Period	САН	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
. 5	1992-1993	CF	5.703	0.1
5	2002-2003	CF	1.845	0.4
14	2000-2001	CF	0.393	1.8
12	1998-1999	cis-1,2-DCE	1.335	0.5
7	2002-2003	cis-1,2-DCE	0.463	1.5
7	1990-1991	cis-1,2-DCE	0.432	1.6
14	1998-1999	cis-1,2-DCE	0.033	20.8
10	2002-2003	cis-1,2-DCE	0.025	27.4
5	1998-1999	MC	2.432	0.3
7	1994-1995	MC	0.733	0.9
7	1990-1991	MC	0.226	3.1
12	2002-2003	MC	0.041	16.7
10	2000-2001	MC	0.036	19.4
14	2000-2001	PCE	0.089	7.8
2	1998-1999	PCE	0.050	13.9
3	2002-2003	TCE	0.990	0.7
7	2002-2003	TCE	0.518	1.3
14	2000-2001	TCE	0.060	11.6
14	2002-2003	TCE	0.020	34.2
10	1996-1997	TCE	0.011	63.9

The biodegradation rate constants listed in Table 5-6 were grouped by chemical to get a Site-wide perspective on the range of biodegradation rates. Statistics describing these biodegradation rates are shown in Table 5-7.

Notably absent from Table 5-7 is a biodegradation rate for CT because none of the CT plumes were considered to be at steady-state. However, an approximate biodegradation rate was estimated for CT by averaging the rates for 10 non-steady-state CT plumes, resulting in a CT biodegradation rate of 0.163 per year.

Grouping the biodegradation rates by chemical and then by time period did not show any consistent patterns of average rate versus time period. For example, the fastest average rates for 1,1-DCA and for 1,1-DCE were during 2002-2003, however, the fastest average rate for 1,1,1-TCA occurred during 1994-1995. For MC the fastest average biodegradation rate was during 1998-1999. Other chemicals lacked



sufficient rate coverage through time to compare. Appendix E provides a sensitivity analysis of biodegradation rates determined for CAHs in groundwater at the RFETS.

Table 5-7 Biodegradation Rate Statistics for UHSU Groundwater by CAHs

САН	Minimum Biodegradation Rate (per year)	Mean Biodegradation Rate (per year)	Maximum Biodegradation Rate (per year)	Sample Standard Deviation	Number of Rate Measurements	
PCE	0.050	0.069	0.089	0.028	2	
TCE	0.011	0.320	0.990	0.431	5	
cis-1,2-DCE	0.025	0.457	1.33	0.533	5	
1,1,1-TCA	0.023	0.238	0.768	0.326	5	
1,1-DCA	0.004	0.304	0.846	0.341	6	
1,1-DCE	0.100	0.579	1.56	0.670	4	
CF	0.393	2.65	5.70	2.74	3	
MC	0.036	0.694	2.43	1.01	5	

CF and MC, both CT daughters, have the two highest mean biodegradation rates at 2.65 and 0.694 per year, respectively. These CAHs also have the highest maximum biodegradation rates. The slowest mean biodegradation rates (per year) are for the parent solvents include PCE (0.07), TCE (0.32), and 1,1,1-TCA (0.24). Corresponding biodegradation mean half-lives (in years) for the CAHs listed in Table 5-7 include 1,1,1-TCA (15.9), 1,1-DCA (30.3), 1,1-DCE (3.0), CF (0.8), cis-1,2-DCE (10.4), MC (8.1), PCE (10.8), and TCE 22.4 years.

The biodegradation rates at RFETS were compared with those measured at other chlorinated solvent sites. Table 5-8 contains rate statistics based on a survey of published field and laboratory biodegradation rate investigations (Aronson and Howard, 1997). It can be seen that all of the RFETS' mean rates are less than 1.0 except for CF at 2.65 per year. The mean biodegradation rates for the non-RFETS sites are much larger (i.e., faster degradation).

Table 5-8 Biodegradation Rate Statistics for Non-Rocky Flats CAH Plumes and Laboratory Studies (based on data from Aronson and Howard, 1997)

САН	Minimum Rate (per year)	Mean Rate (per year)	Maximum Rate (per year)	Number of Investigations	Ratio of Mean Non-RFETS Rate To RFETS Mean Rate
PCE	0.0	9.86	150.	36	143
TCE	0.0	4.02	69.4	78	13
1,1,1-TCA	0.0	3.65	21.5	28	15
1,2-DCA	1.53	2.78	4.02	2	9



САН	Minimum Rate (per year)	Mean Rate (per year)	Maximum Rate (per year)	Number of Investigations	Ratio of Mean Non-RFETS Rate To RFETS Mean Rate
CF	1.46	29.2	91.3	12	11
MC	2.34	2.34	2.34	1	3
CT	0.0	124.	632.	15	760
VC	0.0	6.57	43.8	27	

In summary, CAH biodegradation rates in groundwater at the RFETS are at or near the low end of published biodegradation rate constants. Biodegradation rate constants computed from the 1D method of Buscheck and Alcantar (1995) are believed to overestimate the true rate constant by up to 65% in comparison to a more rigorous 3D method (Zhang and Heathcote, 2003). Thus, the true biodegradation rates at the RFETS are likely to be even lower than those shown in Tables 5-6 and 5-7.

## 5.1.5 Plume Extent and Dynamics Through Time

Numerous isopleth maps were constructed to portray the spatial distribution of CAHs distributions in groundwater at the RFETS for selected time periods. This section introduces the CAH distributions at the RFETS and discusses their behavior. Many isopleth maps are discussed in this section and other useful maps are included in Appendix F.

### 5.1.5.1 Interpreting the Computer-Generated Isopleth Maps

CAHs are manmade chemicals that do not occur ubiquitously, but are detected in monitoring wells located at or downgradient of CAH source areas (e.g., former sites of leaking solvent tanks or drums). Therefore, knowledge of the absence of a CAH a particular well is as important as its presence at another monitoring well. For this reason, the contour maps presented in this section show small open circles indicating the locations of all wells with monitoring data for the mapped analyte, both detected and nondetected, during the time period. Wells with nondetected analyte concentrations are surrounded by white space on the map, while wells with detected concentrations are surrounded by one of the 10 colors (contour intervals) shown in the map legend.

Because clean areas of groundwater where contaminants are not detected are as important as areas with detected contaminants, plume boundaries are drawn halfway between a contaminated well and the closest clean well. However, the data interpolation routine (inverse distance to a power) used both detects and nondetects at face value in interpolating each pixel of the map and assigning it one of the 10 colors.



The presence of CAHs should not be inferred or extrapolated far into regions where there is no data supporting its existence, e.g., along the edges of a map. Therefore, for CAHs the maximum radius of influence of each well was usually set to a radius of 300 feet.

Finally, the RFETS has collected almost 18 years of groundwater monitoring data for some analytes. Each map is a representation of the mean concentrations measured during a two-year time period to minimize seasonality effects. Therefore, there are up to 9 maps for some of the more important CAHs. When viewing these maps the reader should look for new areas of well control that may have identified previously unknown plumes and observe whether plumes have apparently grown or shrunk through time. Interpretations should be made cautiously because hundreds of wells have been abandoned over the years, while numerous new wells have been installed, but not always in the same area. The absence of wells in an area does not necessarily indicate the absence of a plume. However, a plume is probably not present if the map area shows a number of wells surrounded by white space.

Maps for CAH parent solvents and daughters are grouped and discussed in the following sections. The logic behind the map groups is as follows:

- Detects and Nondetects These maps are designed to show maximum amount of available data
   (i.e., both detects and nondetects) and the areal extent of CAHs. They also show well locations
   where the analyte was analyzed but not detected using open black circles surrounded by white
   space;
- Tier II Plume Maps Plumes are defined in this report as areas where aqueous CAH
  concentrations exceed Tier II groundwater action levels. These maps show Tier II concentrations
  and greater. Only well control is shown below Tier II. To facilitate comparing CAH parent
  solvent plumes between time periods, all 9 of the CT plume maps share a common set of contour
  intervals. The PCE and TCE plume maps also share a common set of contour intervals; and
- Tier I Plume Maps Only 6 CAH compounds were found to have plumes with concentrations
  greater than Tier I groundwater action levels during 2002-2003. Maps are included for Tier I
  plumes because they may require further evaluation for potential remedial actions. Such
  evaluations are not performed in this biodegradation screening report.

#### 5.1.5.2 Detects and Nondetects – CT and Its Daughters

Because RFETS was once the largest user of CT in the U.S., the presence and distribution of CT in groundwater is important. Nine maps were prepared to show the distribution of CT plumes as they were known for two-year time periods between 1986 and 2003 (Figures 5-6 through 5-14). The reader may refer to Figure 4-1 for the locations of buildings mentioned in this section.



The 1986-1987 and 1988-1989 maps (Figures 5-6 and 5-7) have limited well control within the IA compared to later periods like 1992-1993 (Figure 5-9). However, the 1986-1987 map shows well developed CT plumes in the East Trenches area and east and south of the 903 Pad.

During 1986-1987, elevated CT concentrations extended southeast of the 903 Pad down the hillside of the 903 Lip Area almost to Woman Creek (Figure 5-6) and plumes occur on all 9 CT maps through 2002-2003 (Figure 5-14). Therefore, CT may occur in the Valley Fill Alluvium at Woman Creek.

Figure 5-6 also shows two other CT plumes in 1986-1987. At least two wells detected a plume on the 881 Hillside about 1000 feet east of B-881 in the area formerly known as OU1. The second CT plume is defined by a single well on the south side of the former Solar Evaporation Pond (SEP) 207C. This may be related to CT use in B-779. The IHSS 118.1 and Ryan's Pits CT plumes were not recognized in 1986-1987 (Figure 5-6).

Comparison of Figures 5-6 and 5-7 shows similar CT plumes, however, Figure 5-7 shows several additional CT occurrences. The most significant CT occurrence is a well east of B-771 and west of Pond 207C. This well, probably P209289, appears to detect the IHSS 118.1 CT plume.

Well control increases during 1990-1991 and 1992-1993 (Figures 5-8 and 5-9) and as a result the number of CT occurrences increases. The CT plumes between B-771 and B-779 are better defined, as are the CT plumes in the East Trenches area. These figures depict the contribution of CT migrating east or northeast from the 903 Pad to the East Trenches Plume. The other portion of the 903 Pad Plume extends southeast towards Woman Creek. Figure 5-9 suggests that the IA had reasonably good well control by 1993, and most of these wells are surrounded by white space (i.e., CT was not detected).

Figure 5-10 shows additional CT occurrences in the central IA during 1994-1995. The 903 Pad and East Trenches plumes continue to exist on the 1994-1995 and 1996-1997 maps. The IHSS 118.1 CT plume is easily recognized on Figure 5-11 for 1996-1997. A large number of wells along the Woman Creek drainage are mostly nondetect in 1994-1995 and 1996-1997, except in an area south of the 903 Pad and in the former OU1.

The CT plume in IHSS 118.1, between B-771 and B-776, is well defined during 1998-1999 (Figure 5-12). A line of wells extend down the former drainage, parallel to Sixth Street, between B-371 and B-771 and suggest that low concentrations of CT occurred in the drainage from an unknown source located east of B-371.

Figure 5-13 (2000-2001) shows several new low concentration CT plumes in the central IA. The plumes are located near B-559, between B-707 and B-750, southeast of B-991, and south of B-664. The East Trenches and 903 Pad plumes continue to be present.



The most recent CT distribution map for 2002-2003 (Figure 5-14) has excellent well coverage because of the Snapshot sampling that was conducted between May and August 2003. During the Snapshot sampling groundwater was collected from several hundred wells that had not been recently sampled. These samples were analyzed for VOCs and for selected redox parameters.

The abundant CT data for 2002-2003 indicate that the IHSS 118.1 plume has not migrated north of B-771 or reached Walnut Creek. However, this plume may be expanding north towards the drainage west of B-771. Most of the wells in the IA do not show any CT detections so there are large areas of white space on Figure 5-14. The greatest concentrations of CT in groundwater during 2003 are at the 903 Pad and at IHSS 118.1. The highest concentration observed during the period was 29,700 µg/L.

The spatial distribution of CF, the first daughter of CT biodegradation, is shown on Figure 5-15. Because of the abundant CT contamination in groundwater at the RFETS, the wide distribution of CF contamination is not surprising. The highest concentrations of CF, about 10,500  $\mu$ g/L, occur at IHSS 118.1 and the 903 Pad. Spatially, most of the CF occurrences mapped at the RFETS have concentrations below 40  $\mu$ g/L.

Figure 5-16 shows the spatial distribution of MC, the daughter of CF during 2002-2003. Only relatively low concentrations, generally less than 10  $\mu$ g/L, of MC are observed in the RFETS groundwater. The maximum concentration shown on Figure 5-16 is 188  $\mu$ g/L at the Mound and 903 Pad.

CM, the third daughter of CT biodegradation, is rarely found in groundwater at the RFETS. The principal CM occurrence is found at IHSS 118.1, where it reaches a maximum concentration of 79  $\mu$ g/L (Figure 5-17). The only other CM occurrences are at the 903 Pad where concentrations are less than 25  $\mu$ g/L.



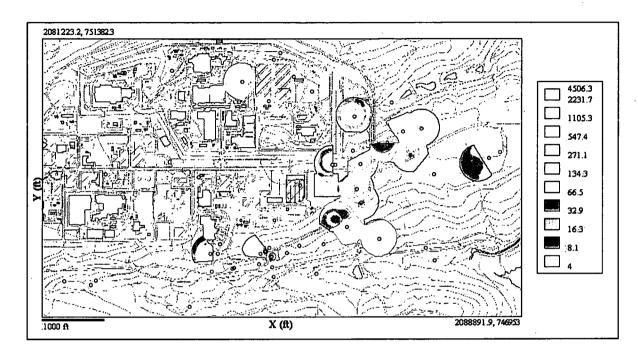
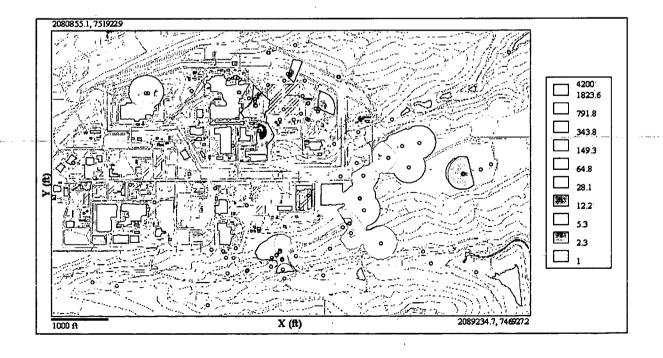


Figure 5-6 Isopleth Map of Carbon Tetrachloride Concentrations (µg/L) During 1986-1987







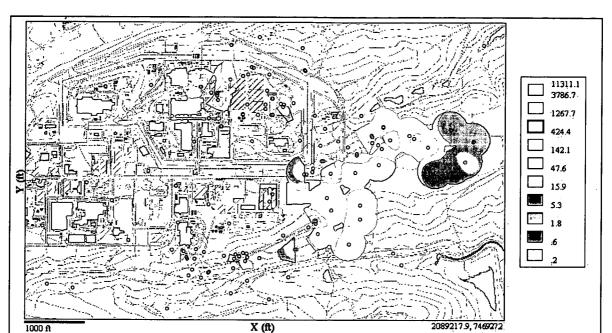
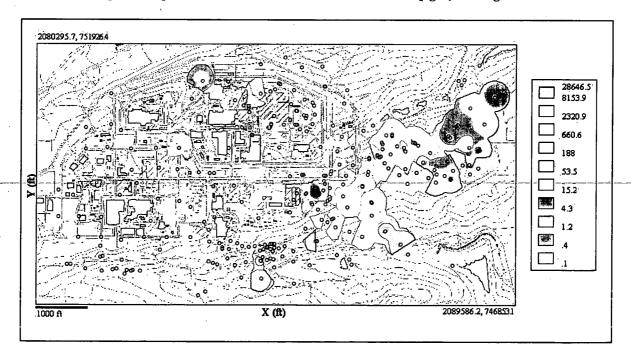


Figure 5-8 Isopleth Map of Carbon Tetrachloride Concentrations ( $\mu g/L$ ) During 1990-1991





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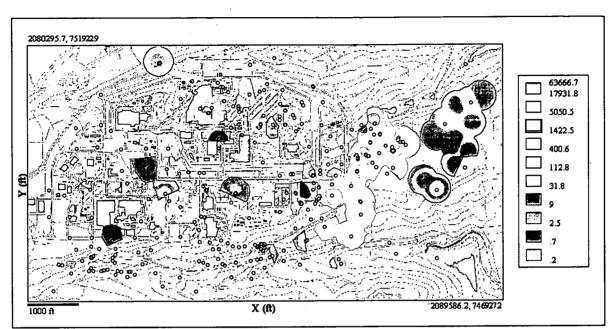
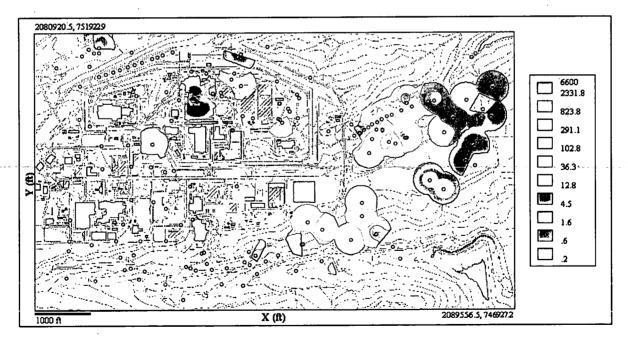


Figure 5-10 Isopleth Map of Carbon Tetrachloride Concentrations (μg/L) During 1994-1995





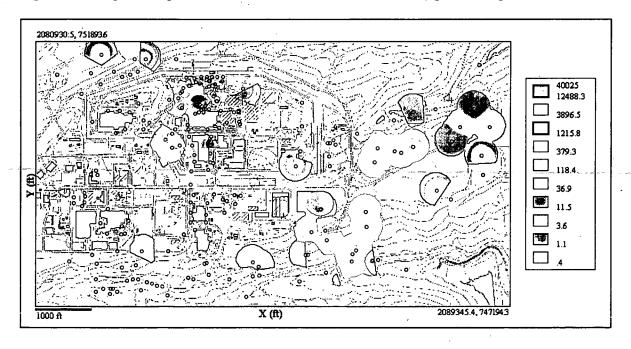
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2081165.5, 7518128

| 43550 | 12740.7 | 3727.3 | 1090.4 | 319 | 933 | 273 | 319 | 933 | 273 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 319 | 31

Figure 5-12 Isopleth Map of Carbon Tetrachloride Concentrations (µg/L) During 1998-1999







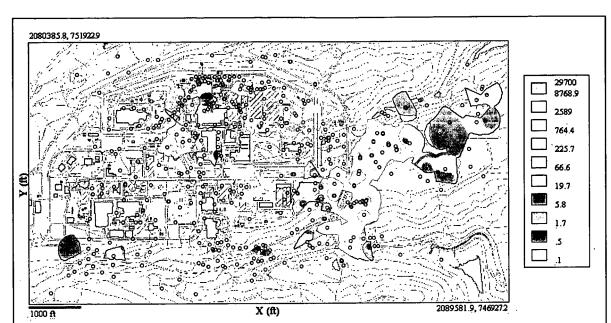


Figure 5-14 Isopleth Map of Carbon Tetrachloride Concentrations ( $\mu g/L$ ) During 2002-2003



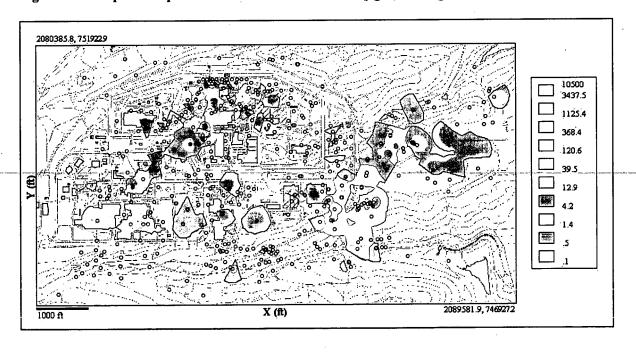




Figure 5-16 Isopleth Map of Methylene Chloride Concentrations ( $\mu g/L$ ) During 2002-2003

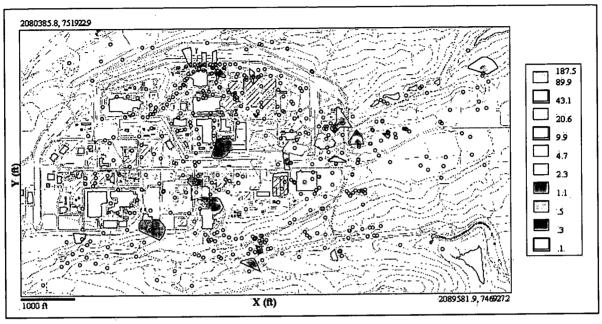
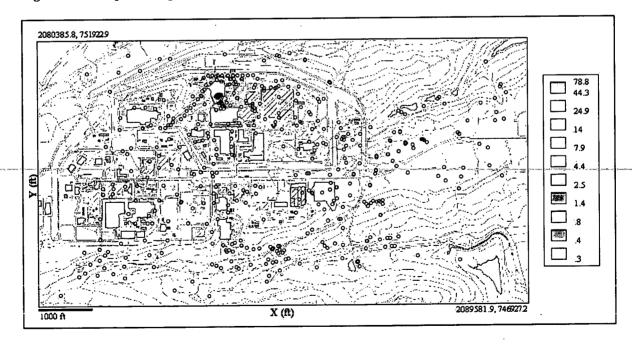


Figure 5-17 Isopleth Map of Chloromethane Concentrations (µg/L) During 2002-2003



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### 5.1.5.3 Detects and Nondetects - PCE, TCE and Their Daughters

Figures 5-18 through 5-26 show concentrations of PCE in groundwater at RFETS between 1986 and 2003. An analogous set of 9 maps has also been created for TCE and are presented as Figures 5-27 through 5-35. If PCE is co-located with TCE it is not easy to determine if the TCE originated from degradation of PCE or if TCE was primary contaminant. Therefore, PCE and TCE maps are discussed together.

Figure 5-18 shows that PCE was found in groundwater in 1986 and was most prevalent east of the 903 Pad. However, during 1986 to 1989, low PCE concentrations also existed at the East Trenches, south of B-881, at the former OU1, north of B-444, and across the Solar Ponds area to B-771 (Figures 5-18 and 5-19).

Figure 5-27 (1986-1987) shows the distribution of TCE plumes. Most of the TCE plumes are co-located with the PCE plumes (Figure 5-18). However, the TCE plume east and north of the 903 Pad extends north to the Mound area. PCE and TCE plumes during 1988-1989 also show similar areal distributions (Figures 5-19 and 5-28).

During 1990-1991, the greatest concentration of PCE in groundwater (48,400  $\mu$ g/L) was at the Mound Site (Figure 5-20). TCE was also elevated at the Mound Site during this period, but the greatest TCE concentrations occurred about 1,000 feet east at the East Trenches, where TCE concentrations exceeded 50,500  $\mu$ g/L (Figure 5-29).

During 1992-1993, the highest PCE concentrations continued to be at the Mound Site and the 903 Pad (Figure 5-21). The highest TCE concentration during this period occurred south of 903 Pad and in the East Trenches area (Figure 5-30). Lower TCE concentrations existed at the 903 Pad and at the Mound Site. An extensive PCE and TCE plume with moderate concentrations extended over an area about 2,500 feet wide northeast of B-444. In general, the PCE and TCE plumes are spatially coincident during this period.

Most of the PCE and TCE plumes were also coincident during 1994-1995 (Figures 5-22 and 5-31). The highest PCE concentration during this period was at the Mound Site and the 903 Pad. The highest TCE concentrations occurred south of the 903 Pad and in the East Trenches area.

During 1996-1997 (Figures 5-23 and 5-32), new wells were installed along the ETPTS. The greatest concentration of TCE observed during this period was 76,000 µg/L south of the 903 Pad. PCE was also present south of the 903 Pad but at lower concentrations. The greatest concentration of PCE occurred at the Mound Site where the concentration was 8,300 µg/L.



During 1998-1999, the largest PCE concentrations occurred at the Mound Site and the 903 Pad. Lower concentrations existed at East Trenches, Ryan's Pit, IHSS 118.1, B-460/B-444, east of B-371, and in several areas around B-883 (Figure 5-24). TCE and PCE plumes generally coexisted (Figure 5-33). However, a TCE plume at B-559 during 1996-1997 and 1998-1999 does not appear to be co-located with PCE. This suggests that the TCE is a parent solvent at B-559. A TCE plume is still visible during 2000-2001 (Figure 5-34).

During 2000-2001, PCE occurrences are noted across the IA and East Trenches. The largest PCE concentrations still occur at the Mound Site (Figure 5-25). The greatest TCE concentrations occur south of the 903 Pad (Figure 5-34).

The most comprehensive maps of the spatial distribution of PCE (Figure 5-26) and TCE (Figure 5-35) are for 2002-2003. These maps are largely based on the Snapshot data and show the current extent of the PCE and TCE plumes which are generally co-located. The highest TCE concentrations occur south of the 903 Pad and at the East Trenches. Groundwater at the Mound Site and the 903 Pad continues to have the highest concentrations of PCE.

Cis-1,2-DCE is the most common TCE biodegradation daughter product. Figure 5-36 shows the spatial distribution and current extent of cis-1,2-DCE during 2002-2003. The cis-1,2-DCE plumes occur across the IA and East Trenches generally in the areas of the known PCE and TCE plumes. The highest cis-1,2-DCE concentration is 2,550 µg/L at the 903 Pad. Other cis-1,2-DCE occurrences are found at B-444/B-460, at B-335, south of B-991, and near the MSPTS. Cis-1,2-DCE concentrations are generally less than 138 µg/L.

Figure 5-37 shows the spatial distribution of VC in groundwater at the RFETS in 2002-2003. VC is produced by reductive dechlorination of cis-1,2-DCE. The highest average VC concentrations observed during this period occur at B-335 (781  $\mu$ g/L) and east of B-551. The maximum VC concentrations occur in well 33502 at 1,200  $\mu$ g/L. Lower VC concentrations are found near the MSPTS (< 31  $\mu$ g/L) Figure 5-37 indicates that VC was not detected in most of the wells sampled during 2002-2003.



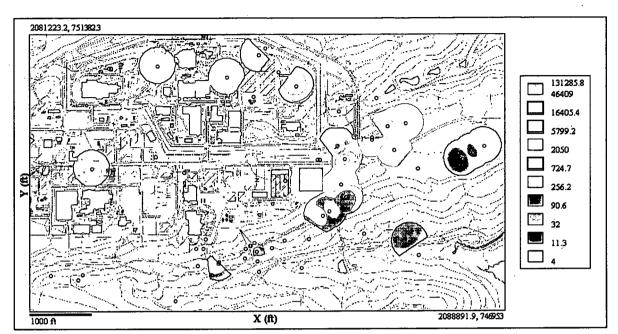
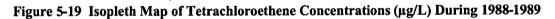
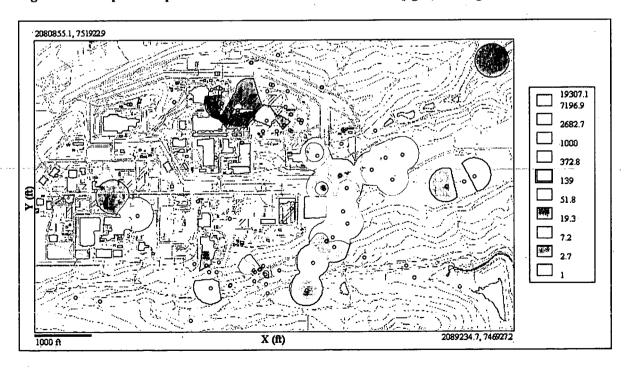


Figure 5-18 Isopleth Map of Tetrachloroethene Concentrations (µg/L) During 1986-1987





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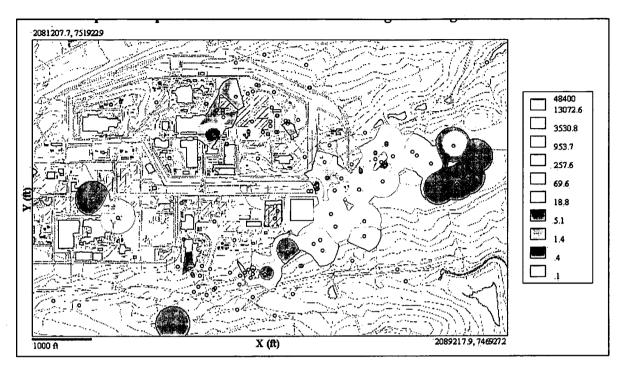
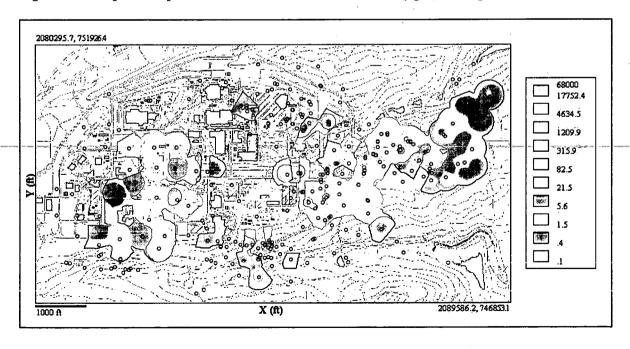


Figure 5-20 Isopleth Map of Tetrachloroethene Concentrations (µg/L) During 1990-1991







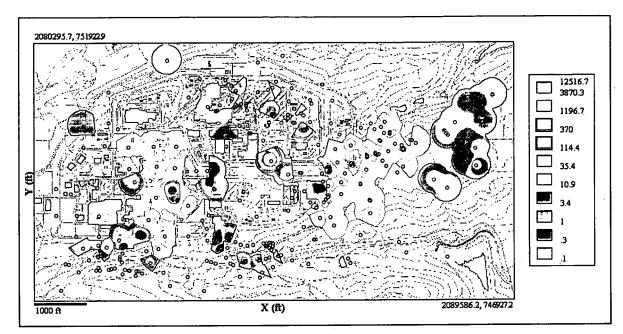
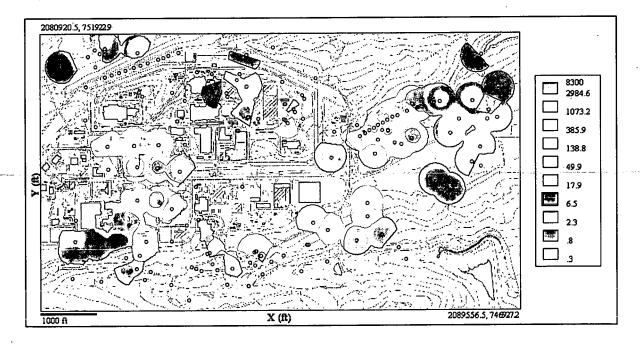


Figure 5-22 Isopleth Map of Tetrachloroethene Concentrations ( $\mu g/L$ ) During 1994-1995





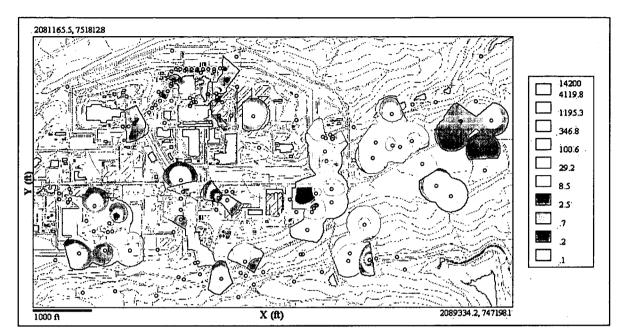
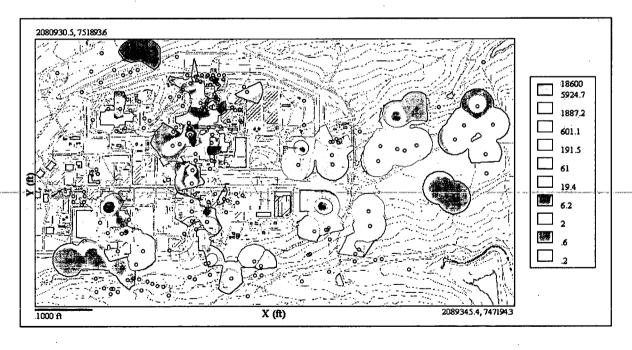


Figure 5-24 Isopleth Map of Tetrachloroethene Concentrations ( $\mu g/L$ ) During 1998-1999







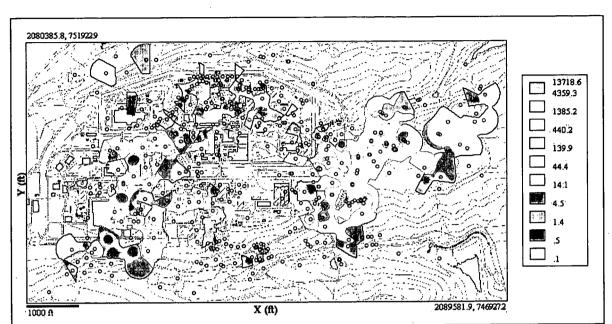
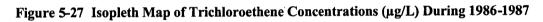
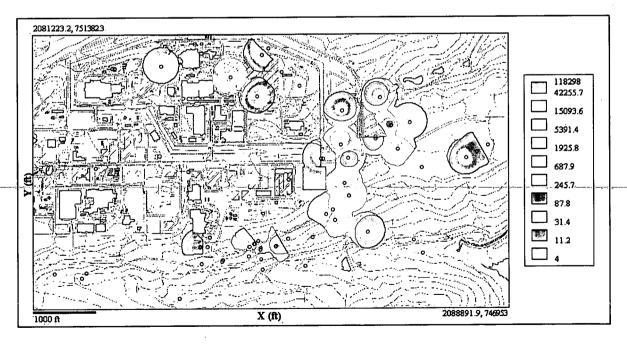


Figure 5-26 Isopleth Map of Tetrachloroethene Concentrations ( $\mu g/L$ ) During 2002-2003







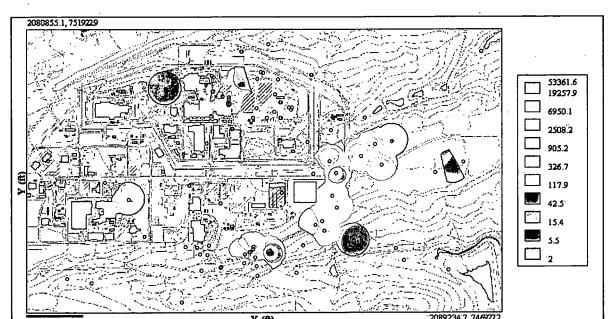
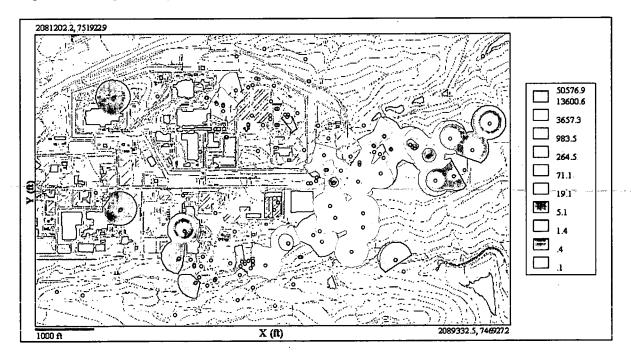


Figure 5-28 Isopleth Map of Trichloroethene Concentrations ( $\mu$ g/L) During 1988-1989

Figure 5-29 Isopleth Map of Trichloroethene Concentrations (µg/L) During 1990-1991



2080295.7, 7519264

| 68035.1 | 17760.7 | 4636.5 | 1210.4 | 316 | 82.5 | 221.5 | 5.6 | 1.5 | 4 | 1.5 | 4 | 1.5 | 4 | 1.5 | 1.5 | 4 | 1.5 | 1.5 | 4 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1

Figure 5-30 Isopleth Map of Trichloroethene Concentrations (μg/L) During 1992-1993



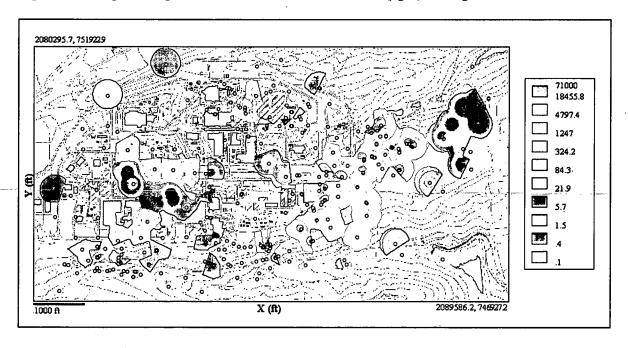


Figure 5-32 Isopleth Map of Trichloroethene Concentrations (μg/L) During 1996-1997

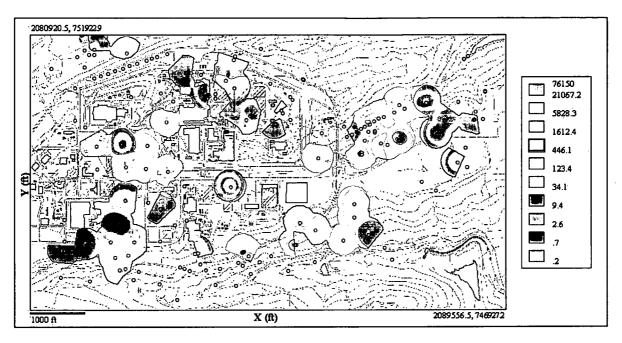


Figure 5-33 Isopleth Map of Trichloroethene Concentrations (µg/L) During 1998-1999

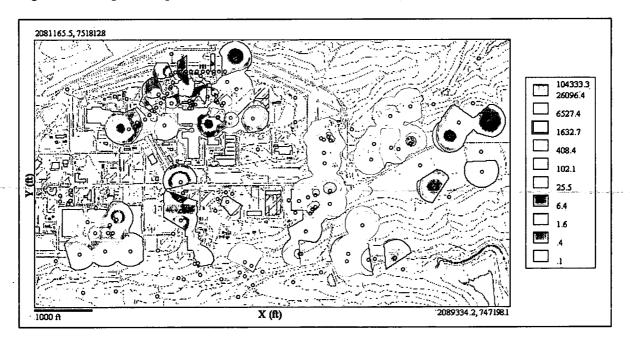


Figure 5-34 Isopleth Map of Trichloroethene Concentrations ( $\mu g/L$ ) During 2000-2001

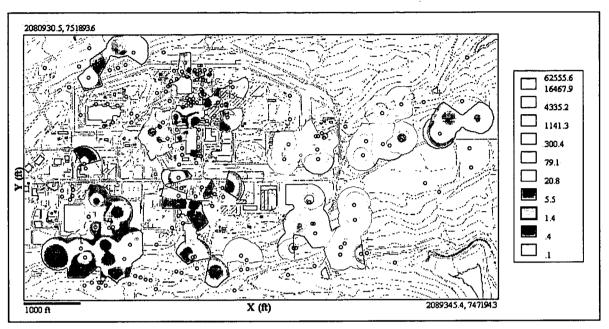


Figure 5-35 Isopleth Map of Trichloroethene Concentrations (μg/L) During 2002-2003

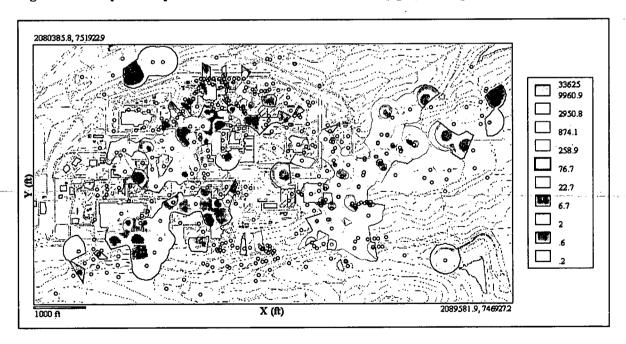


Figure 5-36 Isopleth Map of cis-1,2-Dichloroethene Concentrations ( $\mu g/L$ ) During 2002-2003

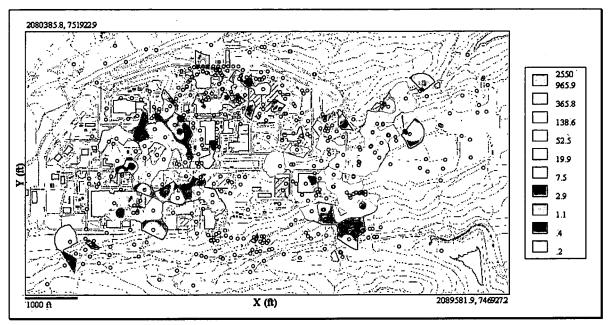
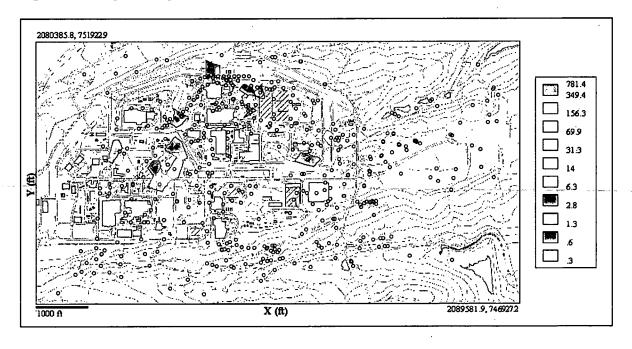


Figure 5-37 Isopleth Map of Vinyl Chloride Concentrations (µg/L) During 2002-2003





## 5.1.5.4 Detects and Nondetects – TCA and Its Daughters

Of the CAH parent solvents used at the RFETS, 1,1,1-TCA is the least prevalent in groundwater. It appears to have been less widely used than PCE and TCE. The short hydrolysis half-life of TCA may also account for its sparse occurrence in groundwater at the Site. Comparison of the spatial distribution of 1,1,1-TCA in 1992-1993 (Figure 5-38) and 2002-2003 (Figure 5-39) shows its sparse occurrence in groundwater and an overall reduction in 1,1,1-TCA concentrations over time. During 1992-1993, the highest average 1,1,1-TCA concentrations occurred at the former OU1 (7,670 µg/L), south of the 903 Pad, and near B-551. Lesser 1,1,1-TCA concentrations occurred south of B-444, at B-881, northeast of B-771, and the East Trenches.

Ten years later in 2002-2003 (Figure 5-39), the areal distribution of 1,1,1-TCA is much less, with the highest average concentrations (610  $\mu$ g/L) occurring in the former OU1, less than one-tenth of its 1992-1993 concentration. During 2002-2003, most wells do not show detectable concentrations of 1,1,1-TCA.

Figure 5-40 shows the distribution of 1,1-DCA in Site groundwater during 2002-2003. This CAH compound is the first daughter of the reductive dechlorination of 1,1,1-TCA. The highest concentration (235  $\mu$ g/L) of 1,1-DCA appears to be at B-551. Some 1,1-DCA is also observed south of the 903 Pad, near B-444, and near B-335, the former fire training center. Other minor 1,1-DCA occurrences are found in the IA and East Trenches area.

Chloroethane (CA) is formed in several ways, but is often results from the reductive dechlorination of 1,1-DCA. Very little CA is found in groundwater at the RFETS. Figure 5-41 shows the areal distribution CA in groundwater during 2002-2003. CA is not detected in most wells, except for a detection of about 2  $\mu$ g/L north of B-551 (southeast of B-371).

In summary, 1,1,1-TCA and its daughters are not commonly detected in groundwater at RFETS, and occur at relatively low concentrations compared to CT, PCE, and TCE. 1,1,1-TCA, in particular, seems to be rapidly attenuating based on a comparison of its areal distribution in 1992-1993 and 2002-2003.



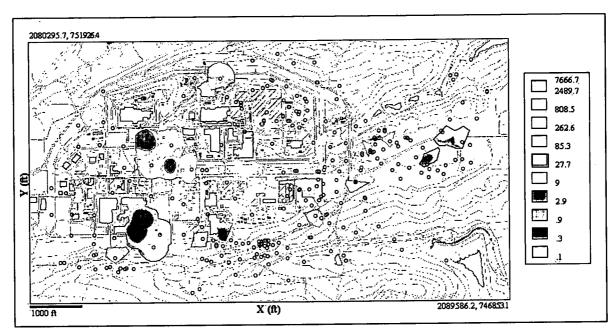


Figure 5-38 Isopleth Map of 1,1,1-Trichloroethane Concentrations ( $\mu g/L$ ) During 1992-1993



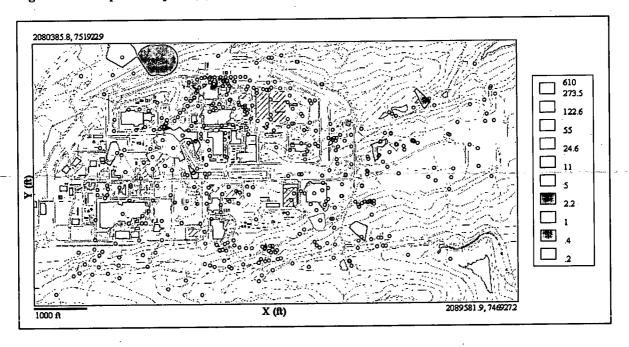




Figure 5-40 Isopleth Map of 1,1-Dichloroethane Concentrations ( $\mu g/L$ ) During 2002-2003

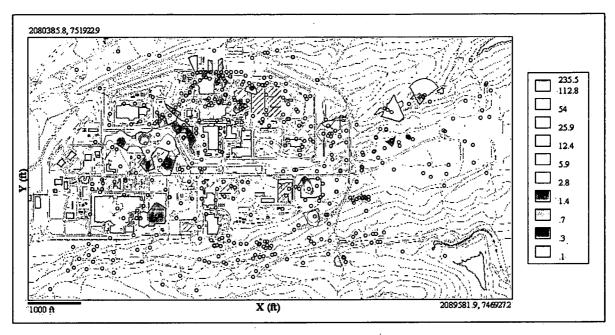
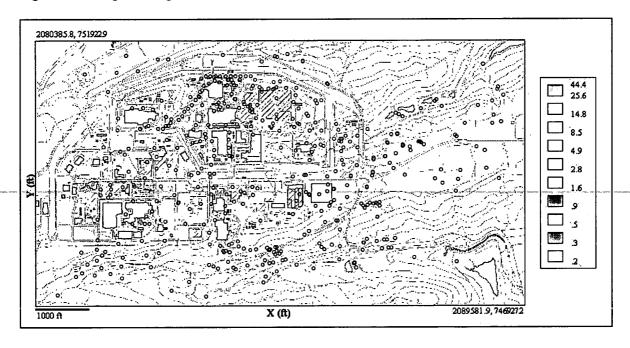


Figure 5-41 Isopleth Map of Chloroethane Concentrations (µg/L) During 2002-2003



## 5.1.5.5 Tier II Plume Maps – CT and its Daughters

CT was the predominant solvent used at the RFETS. The areal distribution of Tier II (5  $\mu$ g/L) or greater CT concentrations is shown as Figures 5-42 through 5-50. Comparison of these maps suggests that the CT plumes have not migrated substantially during the 17 years between 1986 and 2003. Comparison of the 2002-2003 (Figure 5-50) and 1992-1993 (Figure 5-45) maps indicates that the 903 Pad plume concentrations may have attenuated over the decade, but its areal extent is approximately the same during both periods. The IHSS 118.1 plume is better defined on the 2002-2003 map but has probably not significantly increased in concentration since 1992.

CF, a daughter of CT biodegradation, has a Tier II action level of 100  $\mu$ g/L in groundwater. Figure 5-51 (2002-2003) shows several small Tier II CF plumes at the 903 Pad, south of the 903 Pad, at IHSS 118.1, and at the East Trenches. The highest average CF concentration may reach 10,500  $\mu$ g/L at the 903 Pad.

MC is a daughter of CF biodegradation; its Tier II groundwater action level is 5  $\mu$ g/L. Figure 5-52 shows three small Tier II MC plumes in 2002-2003. These plumes are at 903 Pad, the Mound Site, and south of B-991. The highest average MC concentration appears to be about 190  $\mu$ g/L at the Mound Site.

CM, a daughter of MC biodegradation, has a Tier II action level of 6.55  $\mu$ g/L. Tier II CM plumes only occur at IHSS 118.1 and at the 903 Pad during 2002-2003 (Figure 5-53). The highest average CM concentration is about 79  $\mu$ g/L at IHSS 118.1.



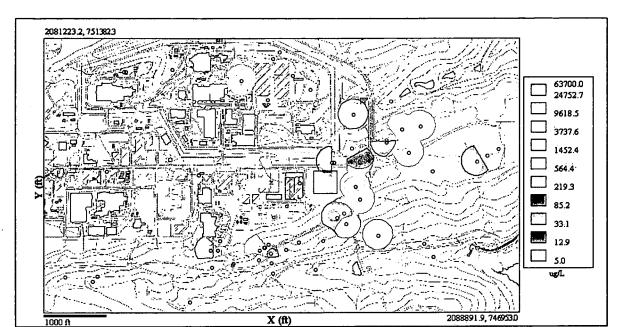
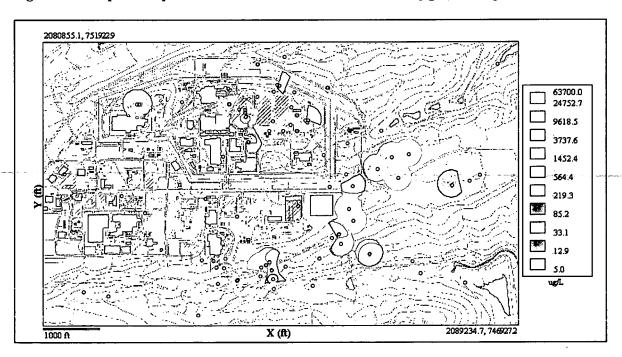


Figure 5-42 Isopleth Map of Carbon Tetrachloride Concentrations (μg/L) During 1986-1987





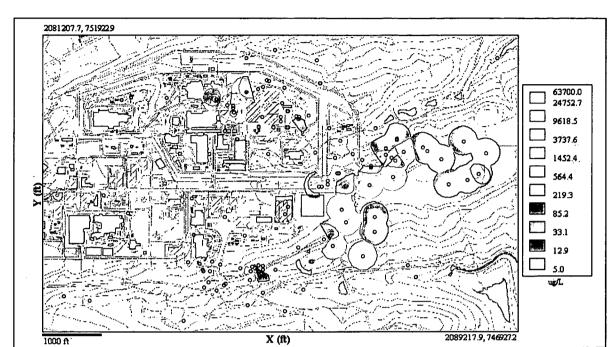
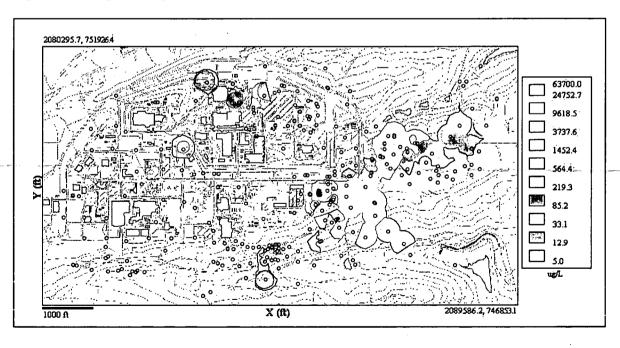


Figure 5-44 Isopleth Map of Carbon Tetrachloride Concentrations (µg/L) During 1990-1991







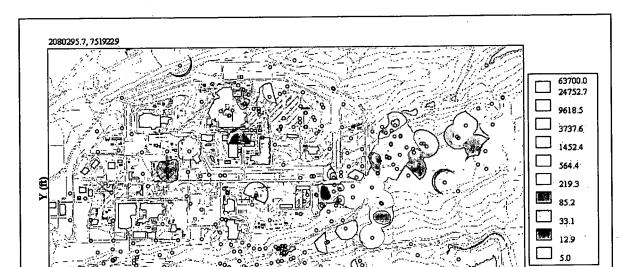
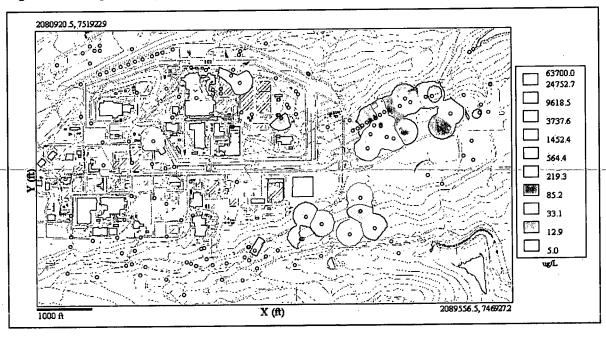


Figure 5-46 Isopleth Map of Carbon Tetrachloride Concentrations (µg/L) During 1994-1995







1000 ft

Review Exemption: CEX-105-01

2089586.2,7469272

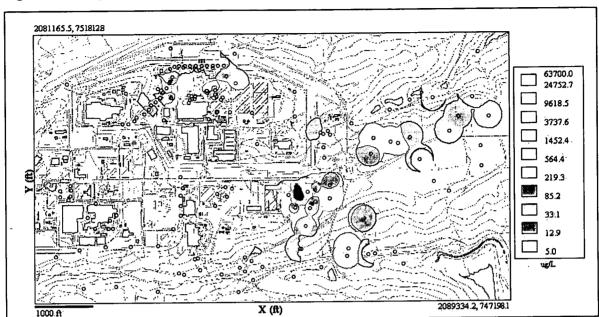


Figure 5-48 Isopleth Map of Carbon Tetrachloride Concentrations (μg/L) During 1998-1999



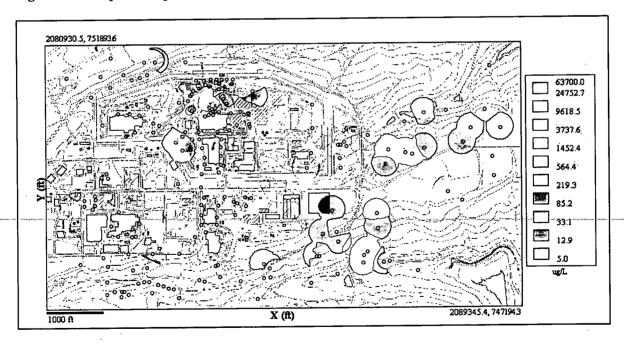




Figure 5-50 Isopleth Map of Carbon Tetrachloride Concentrations ( $\mu g/L$ ) During 2002-2003

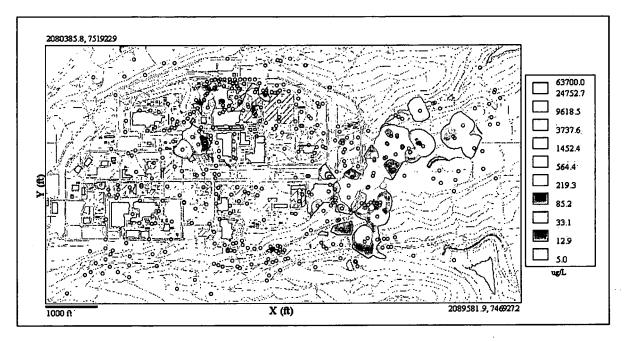


Figure 5-51 Isopleth Map of Chloroform Concentrations (µg/L) During 2002-2003

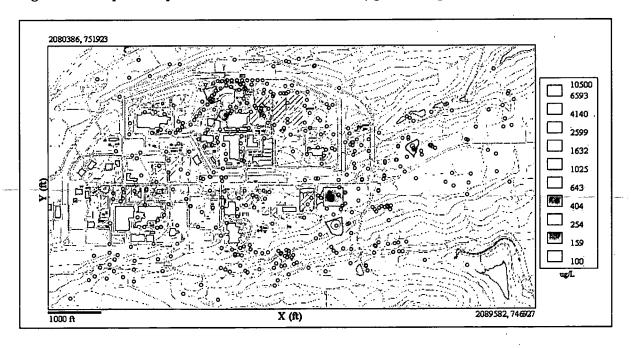




Figure 5-52 Isopleth Map of Methylene Chloride Concentrations (µg/L) During 2002-2003

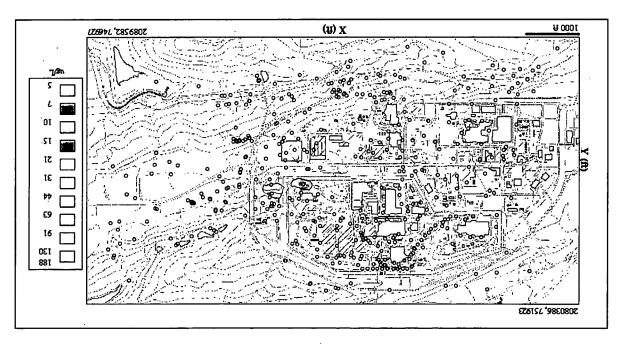
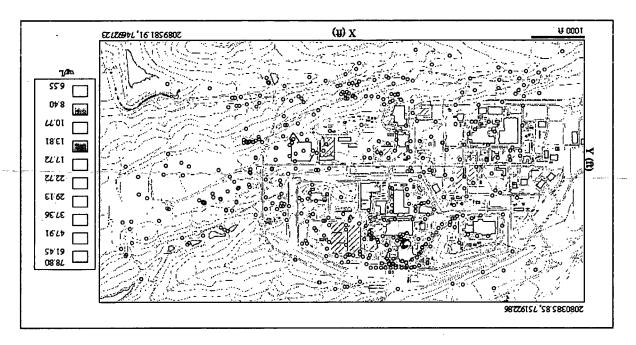


Figure 5-53 Isopleth Map of Chloromethane Concentrations (µg/L) During 2002-2003



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## 5.1.5.6 Tier II Plume Maps – PCE, TCE and Their Daughters

The areal distribution of Tier II or greater PCE plumes is shown as Figures 5-54 through 5-62. The map for 2002-2003 (Figure 5-62) is typical and shows two large PCE plumes located about 2,000 feet apart. The western PCE plume extends from south of B-460 north to B-771. The second PCE plume is associated with the 903 Pad, Ryan's Pit, Mound Site, and the East Trenches and extends to Pond B-2. Hydraulically, it is unlikely that the plume extends across the Walnut Creek drainage to its north side, despite the computer artifact that shows it extending about 200 feet north.

TCE may occur as a primary groundwater contaminant or a biodegradation product of PCE. Figures 5-63 through 5-71 show the areal distribution of Tier II (5  $\mu$ g/L) or greater PCE plumes. Figure 5-71 (2002-2003) shows the current extent of TCE at Tier II or greater concentrations. Two broad areas of TCE plumes occur in the area of the 903 Pad, the Mound Site, and East Trenches areas and near B-460 northeast across the IA to Pond 207A. The crescent-shaped plumes are artifacts of computer contouring.

Several daughter products are possible during the biodegradation of TCE. These include cis-1,2-DCE, trans-1,2-DCE, and 1,1-DCE. Figure 5-72 shows the occurrence of several small Tier II (70 µg/L) or greater plumes of cis-1,2-DCE. These plumes are located at B-335, B-460, B-551, B-991, 903 Pad, and the MSPTS. The highest average cis-1,2-DCE concentration is about 2,550 µg/L at the 903 Pad.

The areal distribution of Tier II (2  $\mu$ g/L) or greater VC concentrations are shown on Figure 5-73. These small plumes occur at B-335, B-551, north of B-771, and at the MSPTS.

Figure 5-74 shows the areal distribution of Tier II (7  $\mu$ g/L) or greater 1,1-DCE plumes in groundwater during 2002-2003. The coincidence of these plumes with TCE suggests that the 1,1-DCE was formed by biodegradation of TCE rather than 1,1,1-TCA. The highest average 1,1-DCE concentrations (about 2,500  $\mu$ g/L) occur at the former OU1, but it is also found near B-551, B-460, IHSS 118.1, and south of the 903 Pad.



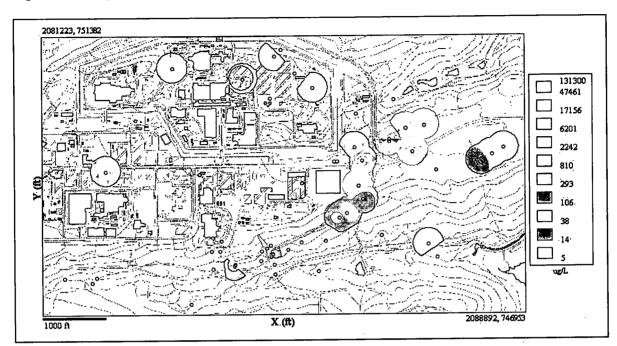
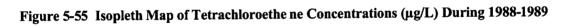
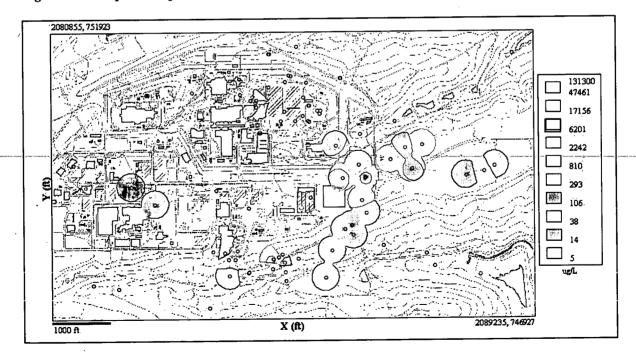


Figure 5-54 Isopleth Map of Tetrachloroethene Concentrations (µg/L) During 1986-1987







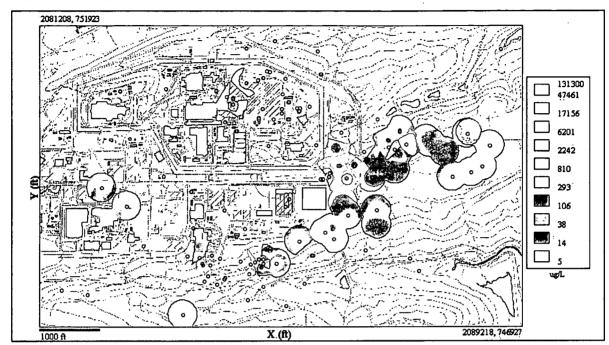
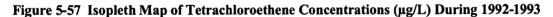
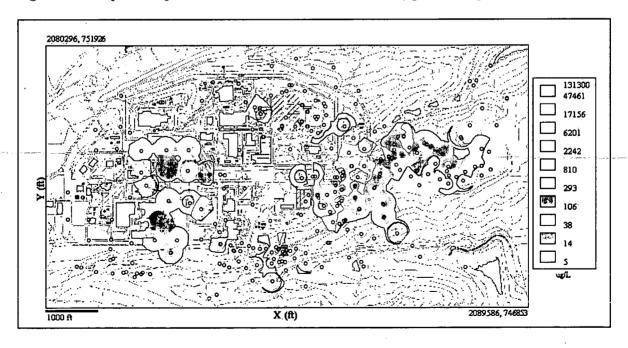


Figure 5-56 Isopleth Map of Tetrachloroethene Concentrations (µg/L) During 1990-1991





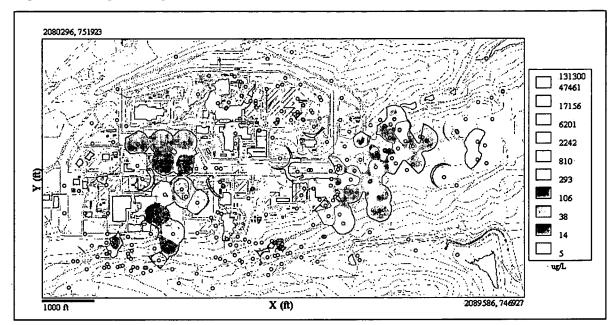
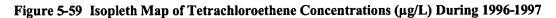


Figure 5-58 Isopleth Map of Tetrachloroethene Concentrations (μg/L) During 1994-1995



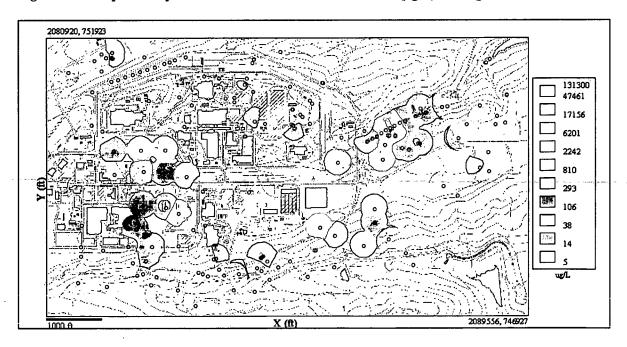
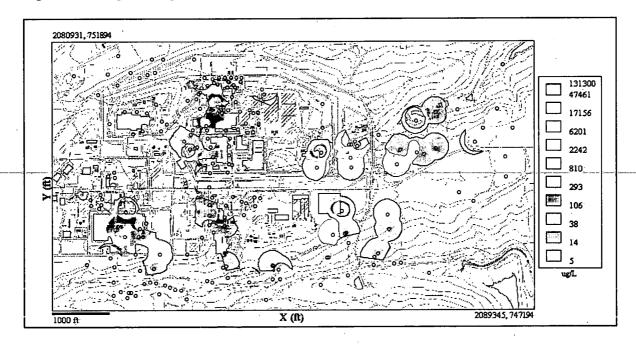


Figure 5-60 Isopleth Map of Tetrachloroethene Concentrations (μg/L) During 1998-1999





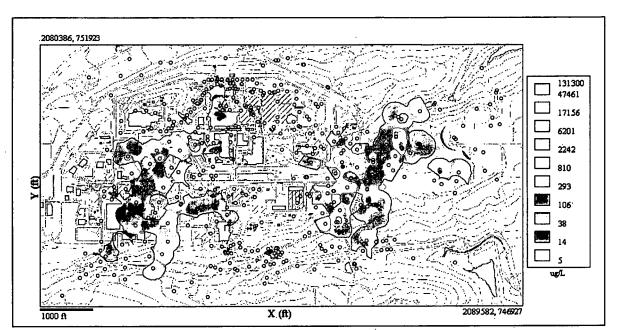
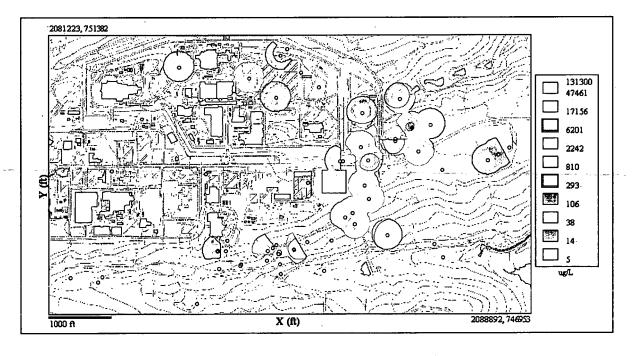


Figure 5-62 Isopleth Map of Tetrachloroethene Concentrations ( $\mu g/L$ ) During 2002-2003





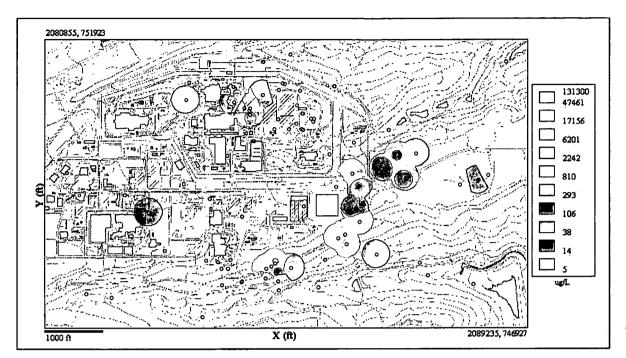
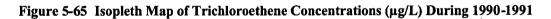
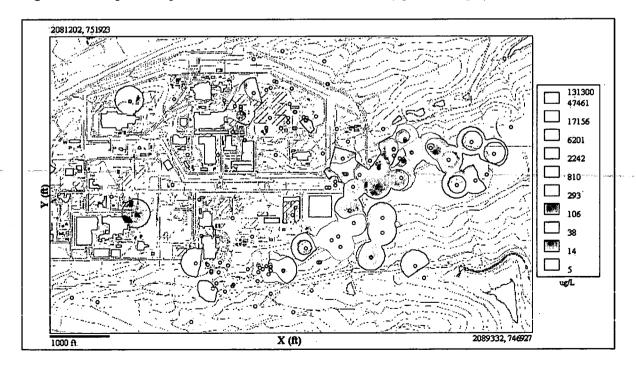


Figure 5-64 Isopleth Map of Trichloroethene Concentrations (µg/L) During 1988-1989





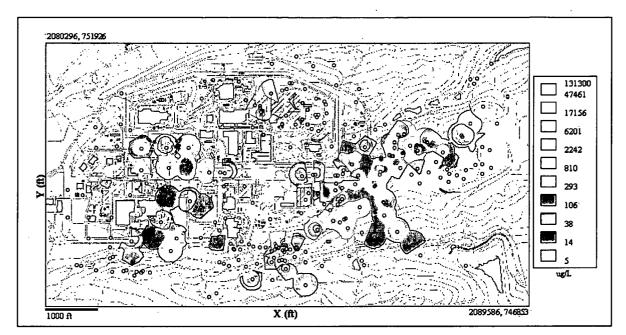
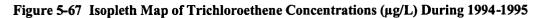
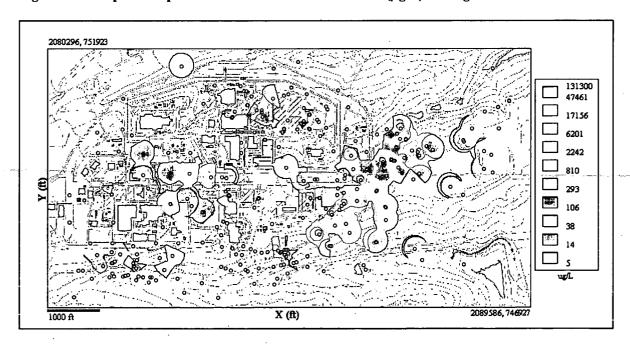


Figure 5-66 Isopleth Map of Trichloroethene Concentrations (μg/L) During 1992-1993







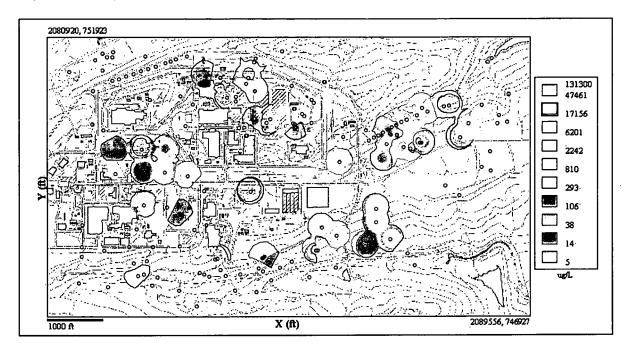
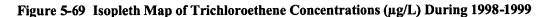
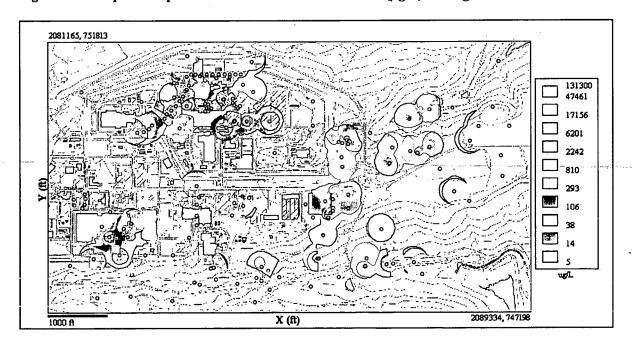


Figure 5-68 Isopleth Map of Trichloroethene Concentrations (μg/L) During 1996-1997







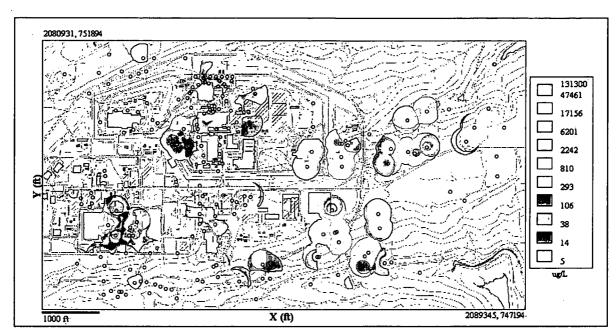
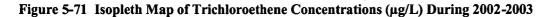
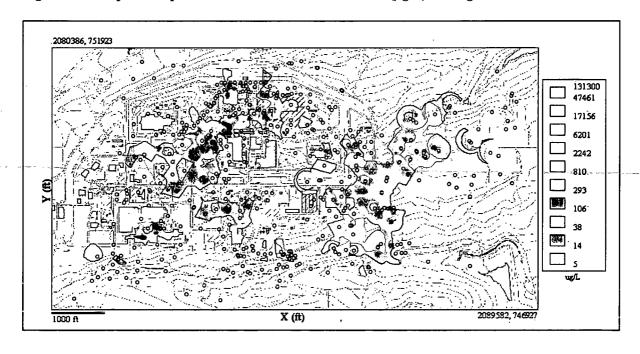


Figure 5-70 Isopleth Map of Trichloroethene Concentrations (µg/L) During 2000-2001







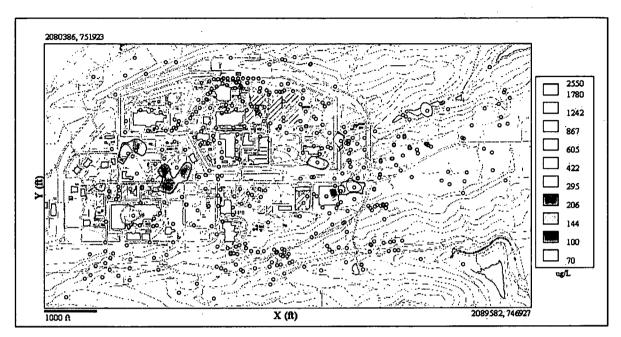
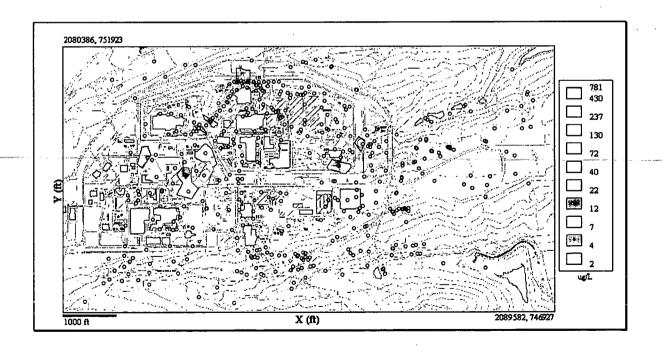


Figure 5-72 Isopleth Map of cis-1,2-Dichloroethene Concentrations (μg/L) During 2002-2003







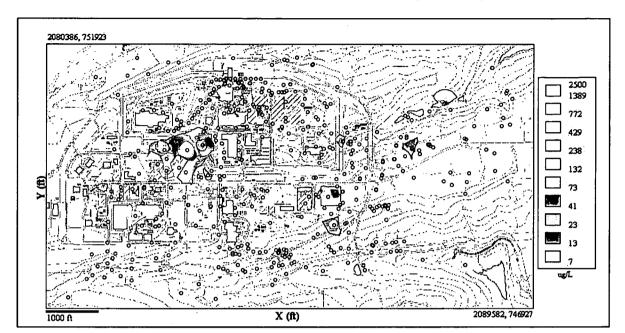


Figure 5-74 Isopleth Map of 1,1-Dichloroethene Concentrations (μg/L) During 2002-2003

# 5.1.5.7 Tier II Plume Maps – 1,1,1-TCA and Its Daughters

Figures 5-75 and 5-76 show the areal distribution of Tier II ( $200 \mu g/L$ ) or greater 1,1,1-TCA for the periods 1992-1993 and 2002-2003. Figure 5-75 shows a small 1,1,1-TCA plume south of the 903 Pad during 1992-1993. The extent of 1,1,1-TCA concentrations above Tier II are more spatially limited in 2002-2003 map (Figure 5-76) where the only Tier II plume occurs at the former OU1 area.

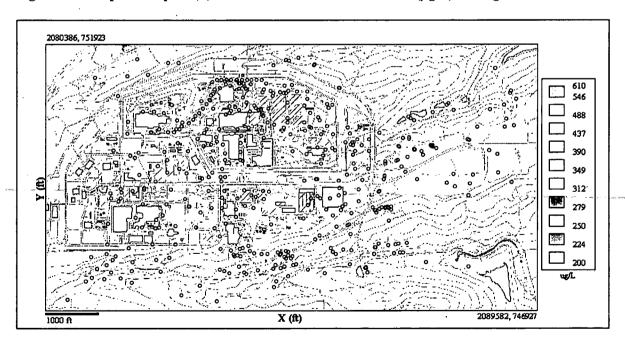
Figures 5-77 and 5-78 shows the current areal distribution of Tier II or greater 1,1-DCA and CM plumes in 2002-2003. Review of this figure indicates that there are no known Tier II or I 1,1-DCA or CM plumes. However, there have been scattered CM detects in the 2002-2003 that were greater than the CM Tier II action level (29.4  $\mu$ g/L).

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Figure 5-75 Isopleth Map of 1,1,1-Trichloroethane Concentrations (μg/L) During 1992-1993



X (ft)



180

1000 ft

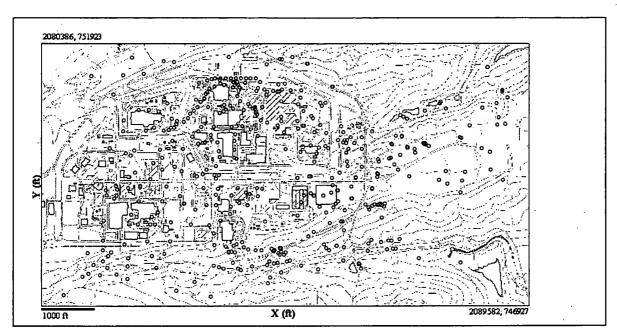
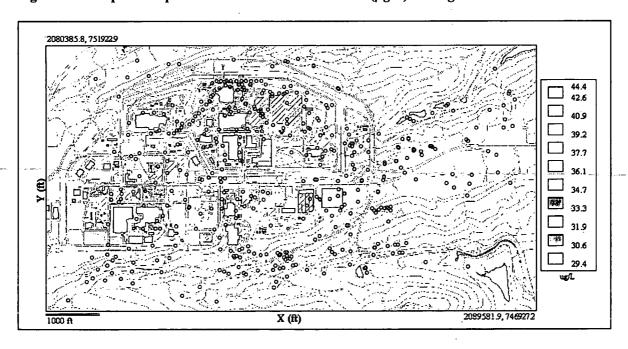


Figure 5-77 Isopleth Map of 1,1-Dichloroethane Concentrations (μg/L) During 2002-2003





### 5.1.5.8 Tier I Plume Maps for CAHs

Current data indicates that only six (6) CAHs (CT, CF, PCE, TCE, 1,1-DCE, and VC) have dissolved groundwater concentrations greater than their Tier I groundwater action levels in 2002-2003. These Tier I plumes are small and occur in IA and East Trenches area. These areas may require additional groundwater evaluations (subsequent to this report) to determine if accelerated groundwater actions are required.

Figure 5-79 shows two Tier I (500  $\mu$ g/L) CT plumes in IHSS 118.1 south of B-771 and the eastern branch of the 903 Pad plume. The highest average CT concentrations are about 29,700  $\mu$ g/L at IHSS 118.1. CT concentrations at the 903 Pad are less than 5,800  $\mu$ g/L, while concentrations east of the 903 Pad are less than 1,700  $\mu$ g/L. A possible third Tier I plume of very small extent is observed at the south end of the former SEP 207C.

A Tier I (>10,000  $\mu$ g/L) CF plume occurs at the 903 Pad during 2002-2003 (Figure 5-80) where its highest average concentrations are about 10,500  $\mu$ g/L.

Figure 5-81 shows two Tier I (>500  $\mu$ g/L) PCE plumes in groundwater during 2002-2003 at and about 400 feet east of the 903 Pad and at the Mound Site. The highest average PCE concentrations range between about 10,000 to 14,000  $\mu$ g/L.

Figure 5-82 shows the Tier I (>500  $\mu$ g/L) plume map for TCE plumes in groundwater during 2002-2003. Eight Tier I TCE plumes are shown on the map. Most of the plumes are small in extent; however, the two largest plumes are in the Ryan's Pit and East Trenches areas. TCE concentrations at the Ryan's Pit plume are as high as 33,625  $\mu$ g/L. Because this plume is upgradient of Woman Creek and within 400 feet of the creek, an additional groundwater evaluation may be needed to determine if an accelerated action is necessary.

The East Trenches plume is located several hundred feet south of Pond B-2. Although VOCs have been measured in B-2 pond water, the majority of this plume is captured by the ETPTS. VOCs in the pond may come from the downgradient portion of the plume that was cutoff when the ETPTS was installed.

Several small Tier I TCE plumes are observed (Figure 5-82) between B-460 and B-444, near B-552, south of Pond 207C, at the Mound Site, at the former OU1, and beneath the 903 Pad. These plumes are limited in areal extent and do not appear to be a threat to surface water.

Figure 5-83 shows the only Tier I (700  $\mu$ g/L) 1,1-DCE plume during 2002-2003 at the Site. This plume is located in the former OU1. The maximum 1,1-DCE concentration in this plume is about 2,500  $\mu$ g/L.



Figure 5-84 shows the only Tier I (200  $\mu g/L$ ) VC plume during 2002-2003. This plume is located around well 33502 near B-335. VC concentrations in this plume have been as high as 1,200  $\mu g/L$ , although the mean concentration for 2002-2003 is about 780  $\mu g/L$ .

Appendix F provides additional isopleth maps for CAHs, degradation products, and degradation indicator analytes concentrations in groundwater not discussed in this section.

Figure 5-79 Tier I Carbon Tetrachloride Plume Map For 2002-2003

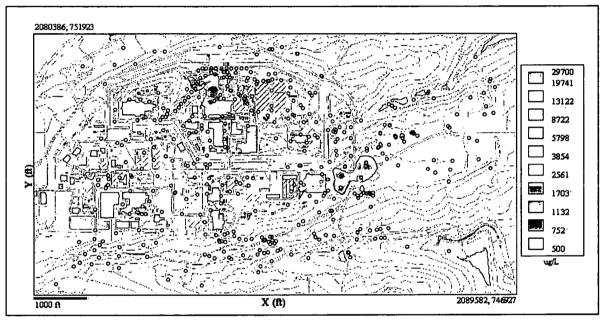




Figure 5-80 Tier I Chloroform Plume Map For 2002-2003

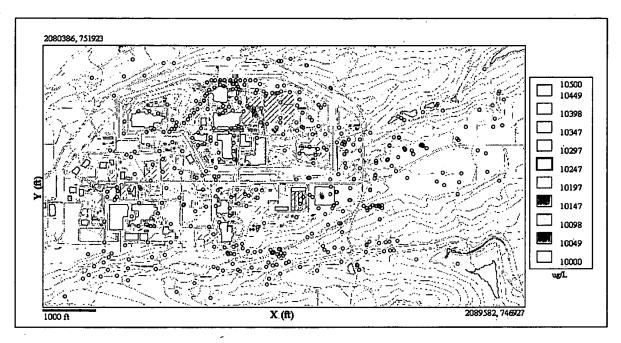


Figure 5-81 Tier I Tetrachloroethene Plume Map For 2002-2003

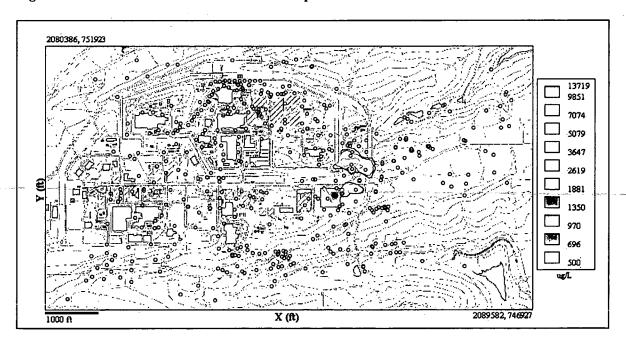


Figure 5-82 Tier I Trichloroethene Plume Map For 2002-2003

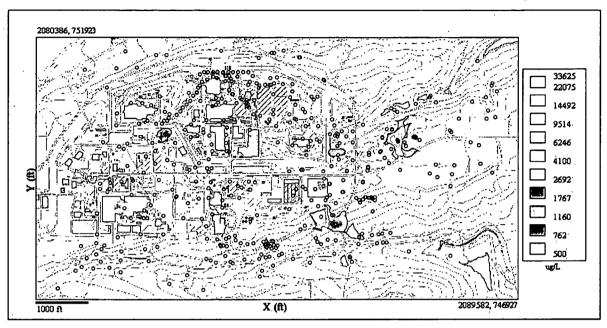
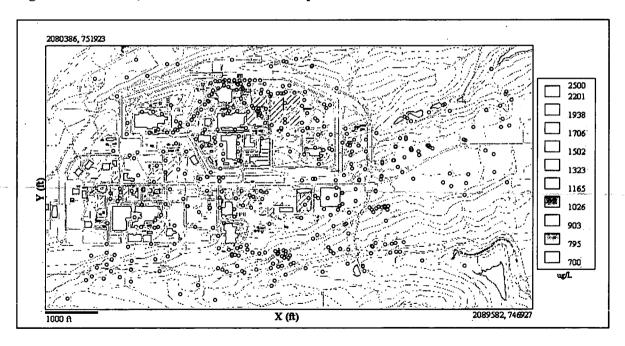


Figure 5-83 Tier I 1,1-Dichloroethene Plume Map For 2002-2003





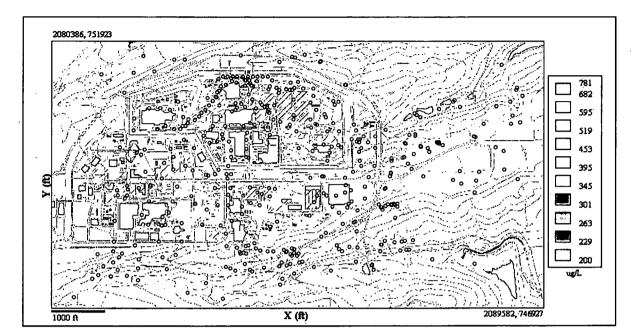


Figure 5-84 Tier I Vinyl Chloride Plume Map For 2002-2003

#### 5.1.5.9 Estimated Plume Lengths During Various Periods

CAH groundwater plume lengths are important. If plumes are growing through time, then they may eventually impact downgradient surface water quality. If plumes are shrinking through time, then natural attenuation processes are reducing contaminant concentrations faster than contaminants leaching from the source area can maintain the plume. If the plume length is not changing substantially (+ or -25%) through time, then it is considered to be at steady-state, which suggests that contaminant attenuation is equal to contaminant source input. The steady-state case is significant because it allows the 1D method of Buscheck and Alcantar (1995) to be used to estimate biodegradation rate constants.

Given monitoring wells in appropriate locations and CAH concentrations, plume lengths can be estimated in several ways. For example, plume lengths can be directly measured from the Tier II plume maps previously discussed. Ln C-vs-D plots can also be used to estimate plume lengths. Plume lengths were estimated for each of the two-year time periods (where possible) to compare the predicted plume length (based on  $K_b$  values) with the estimated plume length during the period. Biodegradation rate constants were estimated for plumes that were predicted to remain at steady-state.

Recall that plume lengths estimated from In C-vs-D plots extend from the well of maximum contaminant concentration along the flowpath downgradient to the Tier II boundary. If Tier II concentrations lie between two wells, then the distance to the Tier II boundary was interpolated. The presence of physical



or hydrologic barriers was not considered in estimating these plume lengths. Plume lengths discussed below should be used cautiously, because:

- Not all wells required to define the full extent of a plume may have been present during a particular period;
- Groundwater may not have been collected and analyzed for CAHs from all relevant wells during the period; and
- Most CAH plumes at the RFETS probably formed prior to the start of widespread groundwater monitoring in 1986 and may have reached their maximum extents during the 1960's or 1970's.

Figures 5-85 through 5-98 are bar charts showing Tier II plume lengths estimated for the time periods between 1986 and 2003. Missing bars indicate the absence of data during the period, not the absence of a plume during the period. All measurements were made along the A flowpath in each PSA evaluated (Figure 3-2). The plume lengths shown were estimated from ln C-vs-D plots. Plumes for compounds within a CAH decay series or family are shown on the same plot. It is likely that some of these Tier II plumes also contain superimposed Tier I plumes of shorter length.

Figure 5-85 shows that the Tier II MC plume in PSA2 was at its greatest estimated length, about 1,600 feet, during 1992-1993. Similarly, the maximum estimated length of the CF plume, about 1600 feet, also occurred during 1992-1993; it is only 500 feet long today. However, the parent CT plume appears to be growing and is estimated to be about 2,000 feet long during 2002-2003.

Figure 5-86 shows the PCE family plumes in PSA2. The PCE and TCE plume lengths are similar and appear to have reached their maximum lengths (about 1,800 feet) during 1998-1999. At present (2002-2003), the plumes are about 1,100 feet long.

The lengths of the CT and PCE plumes in PSA3 are shown on Figures 5-87 and 5-88. The MC plume (Figure 5-87) was about 700 feet long during 2000-2001. Figure 5-88 shows that the TCE plume has been at steady-state during the last decade and currently is about 500 feet long.

The PSA5 MC plume length has steadily receded through time from approximately 1,200 feet long during 1990-1991 to only 200 feet long today (Figure 5-89). Figure 5-90 indicates that PCE plume lengths have been relatively constant during the past decade, ranging in length between 300 and 500 feet. TCE plume lengths in PSA5 reached a maximum during 1986-1987 (or earlier) and have receded to about 400 feet today (Figure 5-90). The PSA5 cis-1,2-DCE plume has been less than 100 feet since 1998.

The PSA7 CT plume may have reached its maximum length (700 feet) during 1994-1995; it is less than 300 feet long today (Figure 5-91). The MC plume may have peaked at about 1,000 feet in length during 1994-1995. Evidence suggests that the PCE and TCE plumes have been growing in PSA7 since 1990



(Figure 5-92). During 1990, the PCE plume length was about 600 feet long, it has grown to about 1,600 feet in 2002-2003.

Figure 5-93 shows the CT family plume lengths in PSA10. The length of the MC plume is about 900 feet, whereas the CT plume is less than 50 feet during 2000-2001. The PSA10 TCE plume has been about 50 feet long during the past 6 years and may be at steady-state (Figure 5-94). The PCE plume was less than 50 feet long during 1992 and grew to about 1,500 feet during 2000-2001; it is currently about 600 feet in length.

Figure 5-95 shows the CT family plume lengths. The CT plume was 300 feet long in 1998-1999, whereas the MC plume was less than 100 feet in length. The PSA12 PCE plume was about 100 feet long in 1998-1999 and appears to have grown to almost 1,100 feet in length by 2002-2003 (Figure 5-96). TCE plume lengths also appear to have increased from about 400 feet during 1998 to 600 feet during 2002-2003.

Figure 5-97 shows that CT plume lengths in PSA14 have been relatively similar between 1998 and 2003. The CF plume has varied between 400 and 600 feet in length since 1998. The MC plume appears to have receded from about 600 feet during 1998-1999 to 260 feet in length during 2002-2003. Figure 5-98 suggests that the PCE plume length may have been at its maximum length (about 500 feet) during 2000-2001, although no data are available prior to 1998. During 2002-2003, the PCE plume is about 400 feet long.

In summary, CAH Tier II groundwater plumes at the RFETS exhibit a range of plume lengths through time and clearly are not all at steady-state. A few plumes have remained at steady-state for extended periods, e.g., TCE in PSA3, PCE in PSA5, and CT in PSA14. Other plumes have receded in length over time, e.g., MC in PSA5 since 1990; whereas, other plumes appear to be growing through time, e.g., PCE in PSA7 since 1990. The bar charts for some plumes exhibit maximum lengths and shapes similar to a histogram for a normally distributed sample set (e.g., CT in PSA7).

Along the same flowpath during the same periods, different CAHs may exhibit different plume lengths. For example, along flowpath A in PSA2 CT plume lengths have generally increased during the past decade, while MC and CF plumes may have reached maximum lengths in 1992-1993 and have since receded to about one-third of their maximum lengths. Because these chemicals share the same flowpath, advective transport alone can not account for the different plume lengths. Different plume lengths along the same flowpath likely result from variations in chemical-specific properties such as K<sub>d</sub>, biodegradation rates, and abiotic degradation rates.



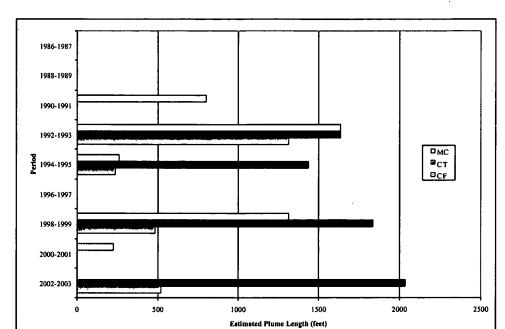
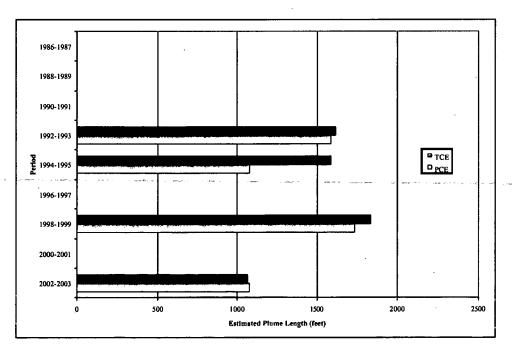


Figure 5-85 Estimated Plume Lengths of CT Family Along PSA2A Flowpath, Various Periods







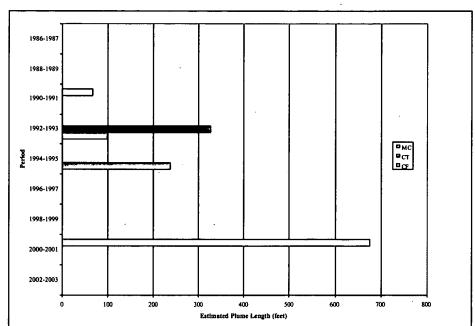
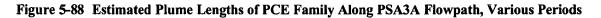
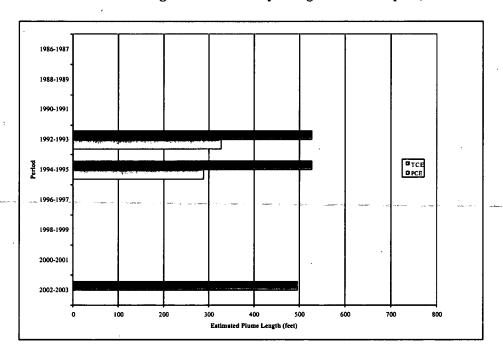


Figure 5-87 Estimated Plume Lengths of CT Family Along PSA3A Flowpath, Various Periods







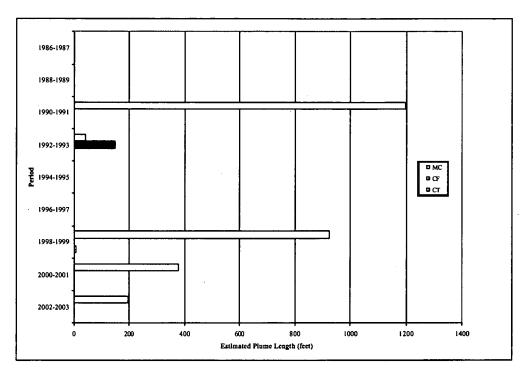
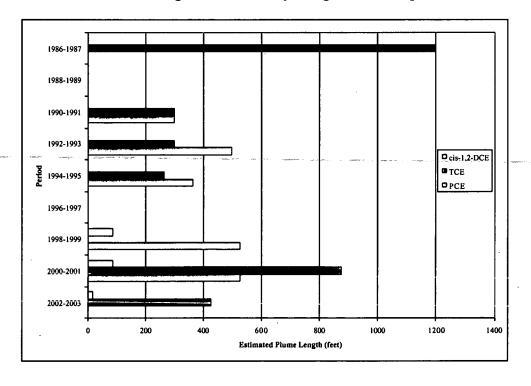


Figure 5-89 Estimated Plume Lengths of CT Family Along PSA5A Flowpath, Various Periods





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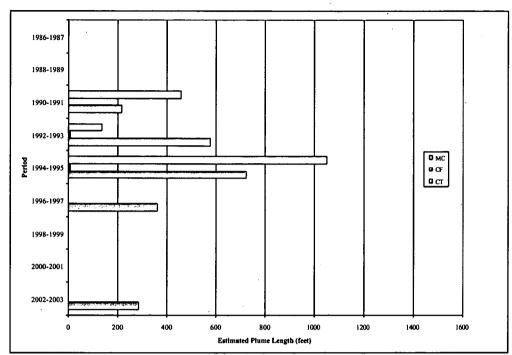
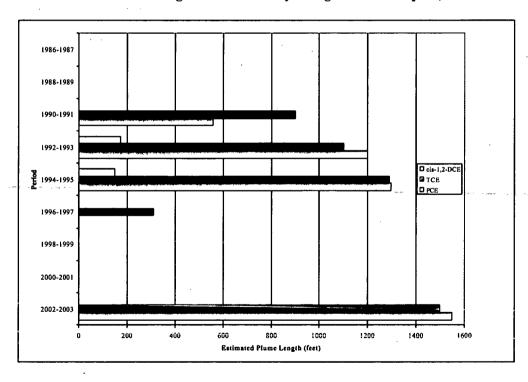


Figure 5-91 Estimated Plume Lengths of CT Family Along PSA7A Flowpath, Various Periods





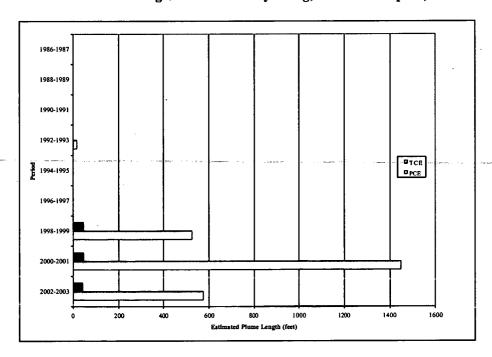


1986-1987
1988-1989
1990-1991
1992-1993
1996-1997
1998-1999
2000-2001
2002-2003

Figure 5-93 Estimated Plume Lengths of CT Family Along PSA10A Flowpath, Various Periods



Estimated Plume Length (feet)



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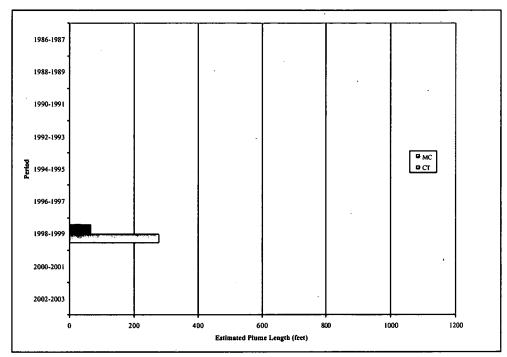
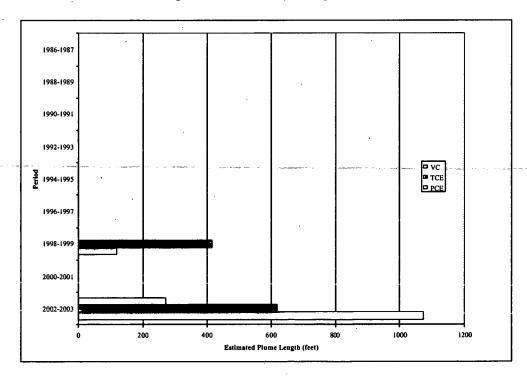


Figure 5-95 Estimated Plume Lengths of CT Family Along PSA12A Flowpath, Various Periods





194

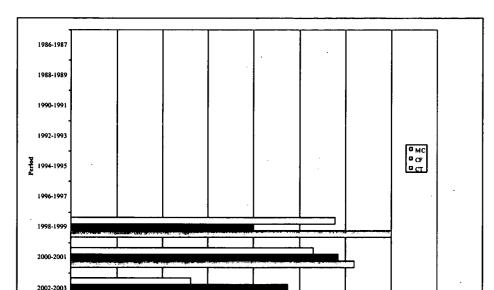
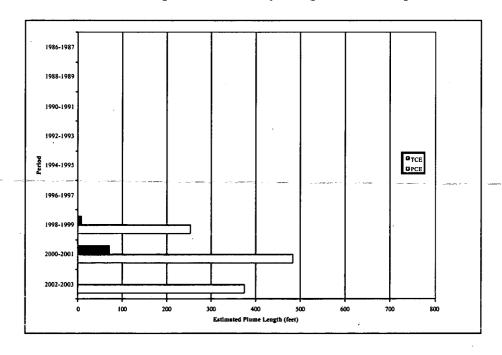


Figure 5-97 Estimated Plume Lengths of CT Family Along PSA14A Flowpath, Various Periods







### 5.1.6 Redox Geochemistry of Groundwater at RFETS

Groundwater ORP (ORP= Eh<sub>Sample</sub> –Eh<sub>Reference</sub>) measurements (Section 3.2.2.2) cannot generally be interpreted in terms of specific redox couples. However, negative ORP measurements (relative to the voltage of a Ag/AgCl reference electrode) are qualitative indicators of reducing conditions. For example, sulfidic waters (with measurable H<sub>2</sub>S) undergoing sulfate reduction have Eh values between –100 mV and –230 mV at pH7 (Lindberg, 1983). The Eh of a Ag/AgCl reference electrode (3N KCl filling solution) at 15°C is +216 mV. Therefore, ORP measurements in the range –316 mV to about –446 mV should be indicative of sulfate reduction.

ORP measurements (434) in UHSU groundwater at the RFETS ranged between -306 to +959 mV, with a mean of +151 mV. Therefore, at the low end, some groundwater at RFETS may be capable of sulfate reduction.

Controlled laboratory experiments on the Eh of oxygenated waters have Eh values in the range +400 to +570 mV, corresponding to ORP readings of +184 to +354 mV at pH7 (Lindberg, 1983). The highest potentials in these experiments were for oxygen saturated water samples. ORP measurements at the RFETS indicate that the UHSU groundwater is relatively oxidizing (mean of +151 mV, maximum of +959 mV) suggesting low to saturated DO concentrations.

Figure 5-99 is an isopleth map of ORP measurements made in the RFETS UHSU groundwater during 2002-2003. The negative or purple colored areas are of most interest, as these areas may indicate where biodegradation is occurring. One of these areas is associated with the 903 Pad and Ryan's Pit where ORP values are as low as -234 mV. On the east side of the IA there appears to be a local ORP high (up to 959 mV) near B-987 that is of unknown origin.

DO is probably the most important redox parameter measured at the Site. Its presence at concentrations above about 0.5 mg/L suggests that biodegradation will be inhibited. About 1,041 DO measurements have been made in UHSU groundwater. These data were collected between April 1991 and August 2003 using a DO probe or Hach DO kit. One hundred and thirty-eight (138) of these measurements exceeded the maximum solubility (10.5 mg/L) of DO in pure water (USGS, 2003) considering the RFETS mean groundwater temperature (13° C) and standard atmospheric pressure. Because these 138 records exceeded the theoretical DO solubility limit, they were excluded from further evaluation. The remaining 903 DO measurements had a mean of 5.68 mg/L and a relatively small standard deviation of 2.48 mg/L.

Cumulative frequency data for DO in UHSU groundwater indicate that 99.99% of the DO concentrations are greater than 0.5 mg/L. About 99.91% of the DO values are greater than or equal to 2 mg/L, and 99.72% are greater than or equal to 4 mg/L. Therefore, more than 99.9% of the wells at RFETS have groundwater that is too oxidizing to support biodegradation.



Figure 5-100 maps the DO distribution in Site groundwater during 1992-1993. DO concentrations ranged from 0.1 to 10.2 mg/L during 1992-1993. Figure 5-101 is a corresponding map of DO concentrations measured during 2002-2003. Both maps are contoured at the same scale to facilitate visual comparison. Comparison shows local differences in DO concentrations between the two figures. However, DO concentrations are generally similar over the decade. Both figures indicate that most of the IA and surrounding area has measurable DO. DO is generally higher in the east half of the IA and across the East Trenches area.

Elevated ferrous iron (Fe<sup>2+</sup>) concentrations are an indication of Fe<sup>3+</sup> reduction and a reducing redox environment perhaps 100 mV more positive (more oxidizing) than that of sulfate reduction at pH7. Ferric iron reduction is often associated with solvent plumes undergoing biodegradation. Ferrous iron data (407 values) were available in UHSU groundwater. These data were collected between May 1999 and August 2003. The mean ferrous iron concentration was 0.7 mg/L with a standard deviation of 3.1 mg/L. This indicates that most of the RFETS UHSU groundwater is relatively oxidizing which limits the occurrence of ferrous iron.

However, a small number of wells have elevated ferrous iron levels (>5 mg/L) that indicate a locally reducing environment suitable for biodegradation. The maximum ferrous iron concentrations occur at well 20598 (31 mg/L) in PSA14, well 1986 in PSA12 (26.8 mg/L), well 33502 (22 mg/L), and well 77492 (21.7 mg/L).

This elevated ferrous iron trend is a good indicator of high biodegradation potential, because the iron coexists with elevated VC and CT concentrations. The highest VC concentrations occur at well 33502 (1,200  $\mu$ g/L) and well 33603 (4,190  $\mu$ g/L), located 200 feet northeast of 33502. The ferrous iron concentration was 2.5 mg/L in well 33603. VC is known to form during biodegradation of 1,1-DCE or cis-1,2-DCE under sulfate-reducing conditions. Elevated ferrous iron also occurs in the area of the CT plume in IHSS 118.1.

Figure 5-102 is an isopleth map of ferrous iron concentrations in groundwater during 2002-2003. Figure 5-103 shows total iron concentrations. Comparison of Figures 5-102 and 5-103 indicates that they show similar dissolved iron distributions. This is expected since the solubility of ferric iron is low in groundwater at near-neutral pH, therefore ferrous iron makes up most of the dissolved total iron measured at the site.

Previously, it was noted that a sulfate-reducing environment is favorable for reductive dechlorination. Thus, it is of interest to look for areas with dissolved sulfide concentrations and/or of anomalously low ratios of sulfate to sulfide. Figure 5-104 shows the concentration of sulfade in groundwater during 2002-2003. Most Site groundwater is very low in sulfade. Low sulfade is expected since DO concentrations are relatively high in most Site wells and sulfade is easily oxidized by DO. However, a few local pockets of



elevated sulfide are shown on Figure 5-104. The maximum sulfide concentration measured (517  $\mu$ g/L) occurred at the eastern end of the East Trenches area.

The mole sulfate/sulfide ratio was computed from analytical data obtained during 2003 and are shown on Figure 5-105. The lowest ratios may indicate active microbial reduction of sulfate ion to aqueous hydrogen sulfide. For example, sulfate reduction may be occurring at well 56594 (the blue-colored low at the bottom left corner of the figure). Several other wells also have very low sulfate/sulfide ratios.

Appendix F provides additional isopleth maps for redox parameters not discussed in this section.

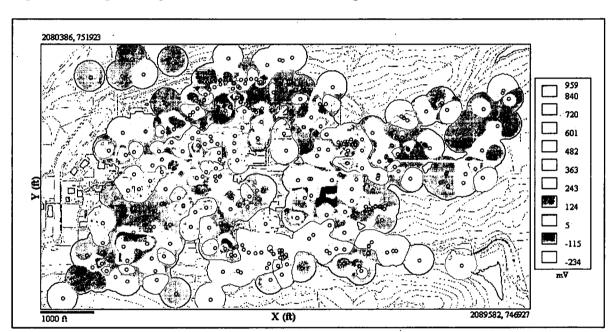


Figure 5-99 Isopleth Map of ORP in Groundwater During 2002-2003



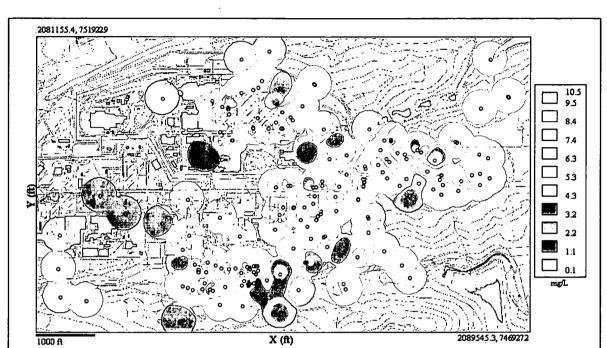
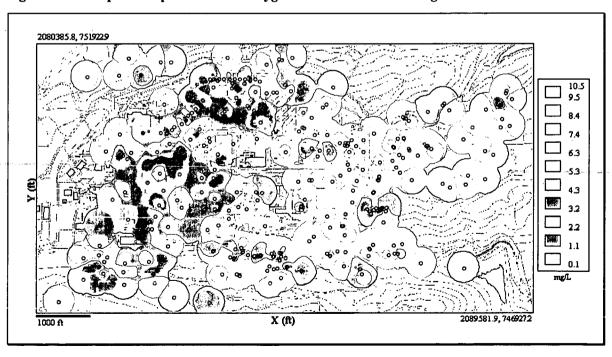


Figure 5-100 Isopleth Map of Dissolved Oxygen in Groundwater During 1992-1993







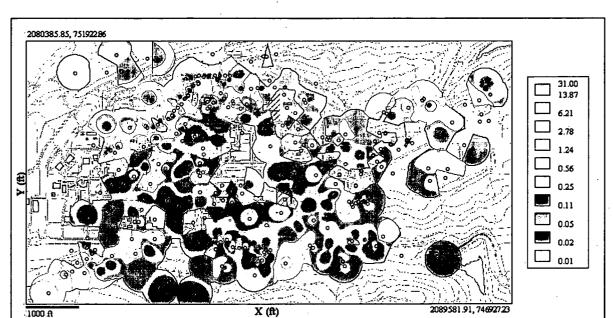
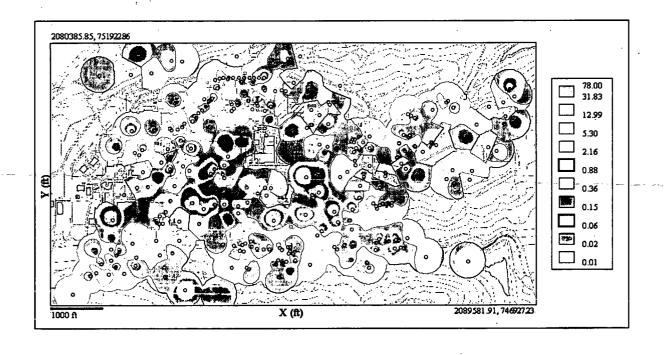


Figure 5-102 Isopleth Map of Ferrous (Fe<sup>2+</sup>) Iron (mg/L) in Groundwater During 2002-2003

Figure 5-103 Isopleth Map of Total Iron (mg/L) in Groundwater During 2002-2003





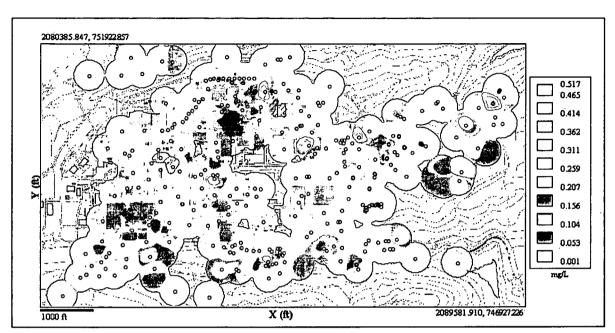
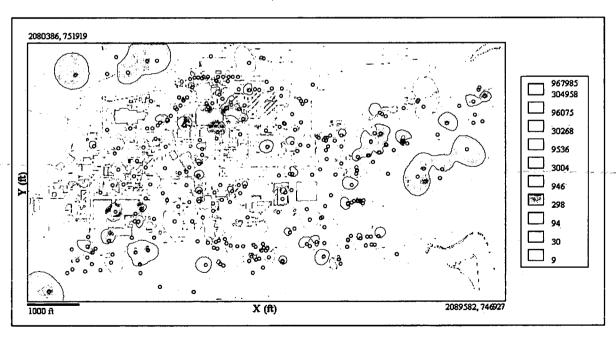


Figure 5-104 Isopleth Map of Sulfide (mg/L) in Groundwater During 2002-2003





### 5.1.7 Geochemistry of Biodegradation Indicator Analytes

CAH destruction, whether by biodegradation, abiotic hydrolysis, or oxidation reactions, results in geochemical changes such as the release of chloride ions. Chloride is a major ion found in most natural groundwaters and it is both ubiquitous and relatively abundant in UHSU groundwater. The background mean concentration of chloride ion in UHSU groundwater is 12,242 µg/L; it was detected in 93% of the background samples (EG&G, 1993). It is difficult to distinguish the additional chloride resulting from CAH degradation superimposed on such a large background concentration. However, chloride concentration were prepared as they may show local increases in chloride concentration especially in the areas of known CAH plumes.

Figure 5-106 shows the chloride concentration in groundwater during 1990-1991. This map displays a wide range of chloride concentrations on a log scale from 4.5 mg/L to 963 mg/L. Given such a large background concentration range, it is difficult to recognize the superposition of local increases in chloride resulting from CAH degradation. It is also desirable to look for long-term changes in chloride concentrations, possibly due to biodegradation. However, during recent years the routine Groundwater Monitoring Program has collected little chloride data. Therefore, a 2002-2003 map is not presented.

Two areas of high chloride concentration are shown on Figure 5-106. These plumes are probably not associated with CAH degradation. One area appears to be associated with the Solar Ponds nitrate and uranium plume. The second chloride plume is located in the area of the 904 Pad where saltcrete was stored. A chloride anomaly that may be associated with chloride derived from CAH degradation occurs at Ryan's Pit south of the 903 Pad. With the possible exception of Ryan's Pit, chloride does not appear to be a very sensitive indicator of CAH biodegradation at the RFETS.

BTEX is commonly found dissolved in groundwater contaminated by gasoline spills or leaking underground fuel tanks. Microbial respiration along with the BOD of fuel hydrocarbons and their degradation products rapidly produce locally reducing conditions in groundwater. The combination of a food source for bacteria and a reducing environment may promote CAH biodegradation (if present). Therefore, the concentration and location of BTEX in groundwater at RFETS may be an indicator of a suitable biodegradation environment. Diesel fuel and hydraulic fluid from lathe coolant should also provide excellent carbon sources for bacteria.

The historical maximum BTEX concentrations are shown on Figure 5-107. The BTEX values mapped were obtained by summing the individual concentrations of individually analyzed BTEX components. Although BTEX is rapidly biodegraded in oxidizing groundwaters, the figure shows that detectable BTEX once existed over much of the IA and East Trenches areas. It also confirms information from the Historical Release Report (DOE, 1992), that there were dozens of fuel spills, leaking tanks, and leaking drums at the RFETS. The highest BTEX concentrations on Figure 5-107 occur near the 903 Pad, which



was a former drum storage site. High BTEX concentrations are also observed at Ryan's Pit, East Trenches, and north of B-777.

CAH biodegradation also increases groundwater alkalinity. Alkalinity is normally measured as total alkalinity by titration with strong acid down to a pH where an indicator dye changes color. In most groundwaters at near neutral pH, the major titrateable component of total alkalinity is bicarbonate ion. RFETS has groundwater quality data for both bicarbonate ion and total alkalinity. Isopleth maps of these analytes may indicate concentration changes spatially associated with CAH plumes undergoing degradation.

Figures 5-108 and 5-109 show total alkalinity concentrations during 1992-1993 and 2002-2003. Comparison of these two figures shows that alkalinity appears to have increased at the 903 Pad over this 10-year period. This increase suggests that biodegradation is occurring at the 903 Pad where CAH solvents were once stored in drums. During other time periods (e.g., 1992-1993), high alkalinity concentrations occur just east of B-991, possibly associated with the Oil Burn Pit.

Figure 5-108 shows an area near B-551 with elevated alkalinity. Groundwater in this area had higher alkalinity during 1992-1993 than it does today. This may indicate a former biodegradation area.

Figures 5-108 and 5-109 show a large range of groundwater alkalinity ranging as high as 2,020 mg/L. As was seen with chloride, it is usually difficult to identify alkalinity produced by biodegradation when it's superimposed on a relatively large and variable background. It is also possible that biodegradation is not proceeding rapidly in most areas of the RFETS and most superimposed alkalinity increases are too small to distinguish.

Appendix F provides additional maps of biodegradation indicator parameters not discussed in this section.



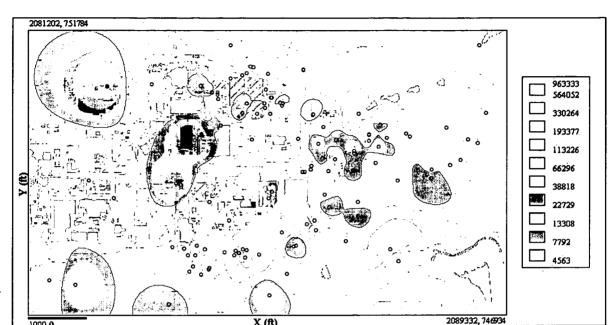
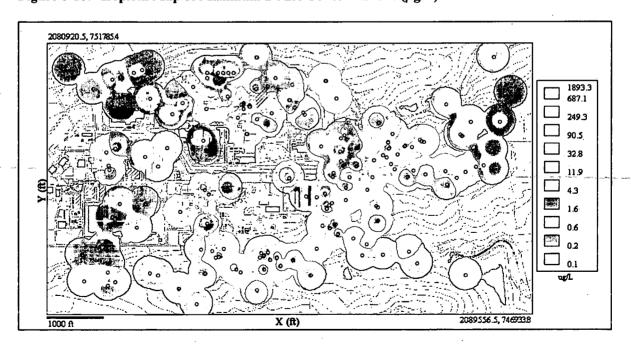


Figure 5-106 Isopleth Map of Chloride ( $\mu$ g/L) in Groundwater During 1990-1991





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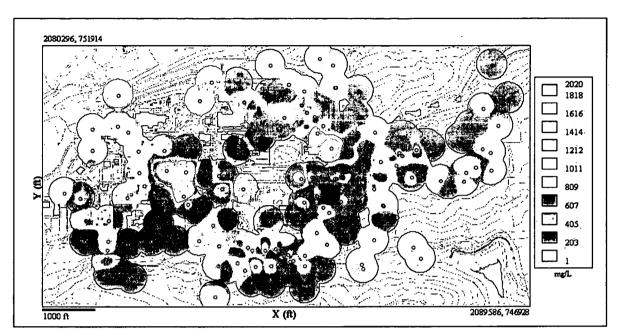
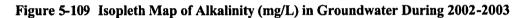
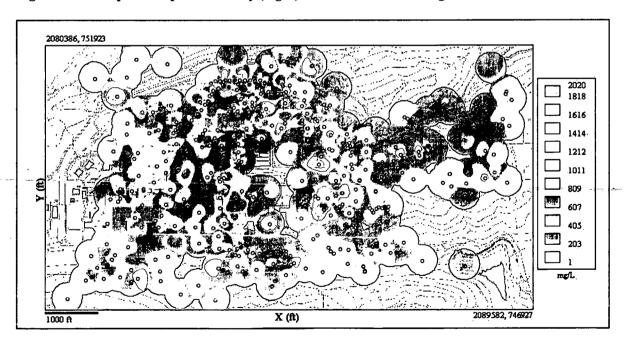


Figure 5-108 Isopleth Map of Alkalinity (mg/L) in Groundwater During 1992-1993







### 5.1.8 Molar Changes in CAH Plumes Through Time

Another line of evidence for the occurrence of CAH natural attenuation is to identify decreases in CAH chemical mass over time. Changes in CAH mass over time were determined on a Site-wide basis by calculating the mean CAH concentrations at individual wells during 1992-1993 and 2002-2003. If natural attenuation is occurring, measurable, and possibly large decreases in mass should be observed between the two periods. Figures 5-110 and 5-111 show the total CAH mass in groundwater for the two periods.

The mean concentrations of individual CAH compounds in groundwater were computed for individual wells during 1992-1993 and 2002-2003. Molecular weights were used to convert concentrations from  $\mu$ g/L to micromoles/liter. These latter units are also known as  $\mu$ Mole/L, micromolar, or  $\mu$ M concentrations.

CAH concentrations could have been summed in  $\mu g$  units, but each CAH compound has a different molecular weight. One molecule of parent solvent degrades to one molecule of daughter product of lower mass. Changes in  $\mu g$  would reflect changes in the relative proportions of parent and daughter compounds. However, changes in moles actually indicate the numbers of contaminant molecules in the groundwater. When the  $\mu$ Mole number decreases through time it indicates a net CAH loss through natural attenuation, regardless of molecular identity.

Figure 5-110 shows the molar CAH concentrations at the Site during 1992-1993. Concentrations up to 624  $\mu$ Moles/L of CAHs were measured in groundwater during this period. The areas with the highest CAH concentrations occur at the 903 Pad and Ryan's Pit. Elevated CAH concentrations also occur at the East Trenches south of Pond B-1. Figure 5-111 shows the molar CAH concentrations at the Site during 2002-2003. The maximum molar concentration in any well during this recent period was 266  $\mu$ Moles/L Comparison of these figures shows similar molar CAH concentration distributions.

To determine if natural attenuation has reduced the total CAH mass, the total μMoles of CAHs at each well were compared between the two periods. The CAH mass difference was determined by subtracting the CAH mass in 1992-1993 from the CAH mass in 2002-2003 at each well. Data for this comparison were available at 122 wells. Figures 5-112 and 5-113 show the total CAH mass decreases and increases over the past decade, respectively.

Figure 5-112 shows the CAH mass decreases across the Site. Mass decreases occurred at 91 wells. These decreases represent areas where the CAH concentrations are naturally attenuated (i.e., CAH mass is reduced) which occurs essentially site-wide. The average decrease in molar concentrations at these wells was  $14.05 \mu Moles/liter/well$ . Areas with the largest CAH mass decreases includes the 903 Pad, Ryan's Pit, East Trenches, and east of B-771. The greatest mass loss in any area was  $534 \mu Moles/L$  at the 903 Pad.



Figure 5-113 shows the areas where CAH mass loss has not occurred(i.e., mass increases have occurred). Mass increases occurred at 31 wells. The average increase in mass was relatively small at  $3.54 \,\mu$ Moles/liter/ well. In general, these local areas of increasing concentrations are geographically similar to the attenuating areas. This suggests that degradation rates vary widely from well to well at the RFETS. The largest mass increase was  $50.3 \,\mu$ Moles near the  $903 \, Pad$ .

If the changes in mass of all 122 wells are summed, the net change is an overall mass loss of 1,169  $\mu$ Moles/122 liters, or 9.6  $\mu$ Moles/ liter/ well. This is evidence that overall CAH plumes at the RFETS are undergoing natural attenuation. The overall decline is actually a rate, 9.6  $\mu$ Moles/ liter/ decade at each well. Therefore, the site-wide average molar CAH attenuation rate is 0.96  $\mu$ Mole/ liter/ year.

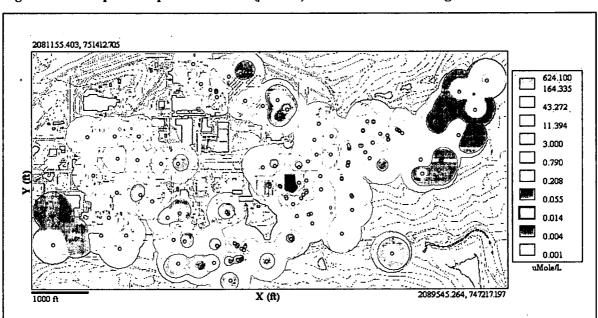


Figure 5-110 Isopleth Map of Total CAH (µMoles) in Groundwater During 1992-1993



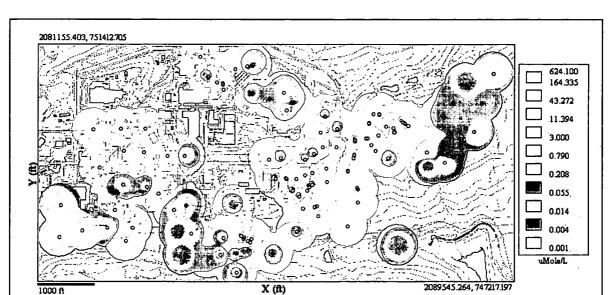
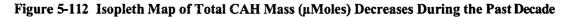
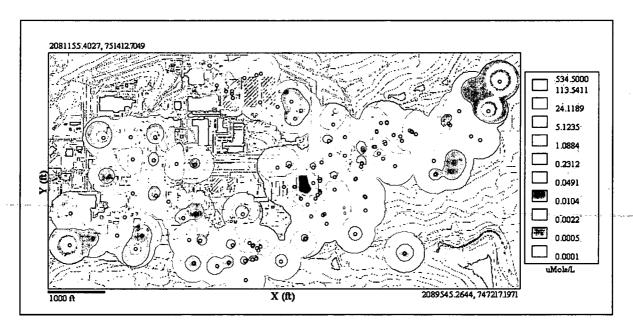


Figure 5-111 Isopleth Map of Total CAH (μMoles) in Groundwater During 2002-2003







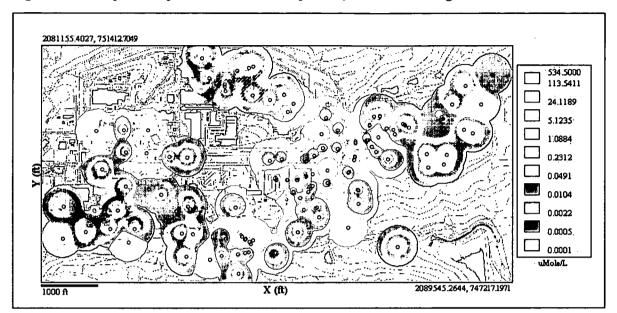


Figure 5-113 Isopleth Map of Total CAH Mass (µMoles) Increases During the Past Decade

### 5.1.9 Other Lines of Evidence for Biodegradation

The ratios of the cis and trans stereoisomers of 1,2-DCE have been used as an indicator of biodegradation. The man-made solvent is a mixture of cis- and trans-1,2-DCE. The isotopic composition of this mixture varies with the manufacturing process. In contrast, biodegradation produces mainly cis-1,2-DCE (EPA, 1998). Low concentrations of trans-1,2-DCE and of 1,1-DCE are also produced by biodegradation (Bouwer, 1994). However, the cis/trans ratio is typically greater than 25 to 1 in groundwater where biodegradation is actively proceeding.

Figure 5-114 shows the maximum ratio cis-1,2-DCE/trans-1,2-DCE in groundwater at RFETS. The cis/trans ratio was computed for each well and sampling event with detect-data for both isomers. The trans isomer is not commonly detected in analytical data from the last decade. Figure 5-114 indicates that most of the wells had high cis/trans ratios, ranging between 26 and 684. These high ratios suggest that biodegradation is occurring in these areas.

Plots of CAH molar ratios (other than cis/trans), e.g. DCE/ TCE, versus source distance have also been used as an indicator of biodegradation (Murphy and Morrison, 2002). For example, the DCE/TCE ratio may increase during anaerobic biodegradation if TCE degrades faster than DCE, but farther down the flowpath the ratio may decrease under aerobic conditions. Numerous CAH ratios were computed during this evaluation, however, trial plots were difficult to interpret and do not appear to provide clear evidence of degradation or its absence.



A theoretically straightforward approach to visualizing natural attenuation is illustrated by the hypothetical data of Figure 5-115. This figure shows that CAH concentrations are expected to approximately attenuate as a first-order decay process. Natural attenuation processes such as biodegradation, sorption, advection, and dispersion should decrease CAH concentrations with increasing migration distance along a flowpath.

This evaluation tried this graphical approach of comparing concentration versus distance data at various time intervals. Figure 5-116 is an example for PCE in groundwater at PSA2B. The oldest period should have the highest PCE concentrations and the most recent period the lowest concentrations of PCE. However, the overlapping concentration versus distance curves in Figure 5-116 suggests that the real-world situation in groundwater at RFETS is more complex. Consequently, this method of evaluation was not widely applied in this evaluation.

2081676.6, 751431.8

| G84.0 | 356.1 | 185.4 | 96.5 | 50.2 | 26.2 | 13.6 | 7.1 | 1.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0

Figure 5-114 Isopleth Map of Maximum cis-1,2-DCE/trans-1,2-DCE Ratios, 1986-2003



Figure 5-115 Hypothetical Response of CAHs Undergoing Natural Attenuation

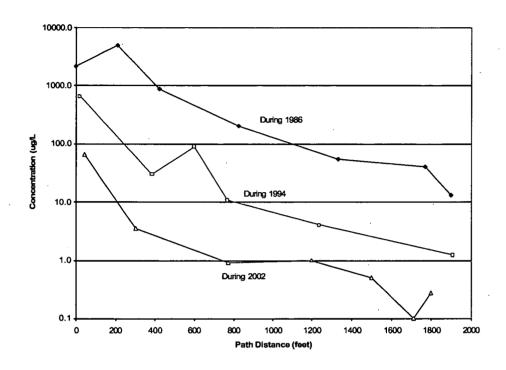
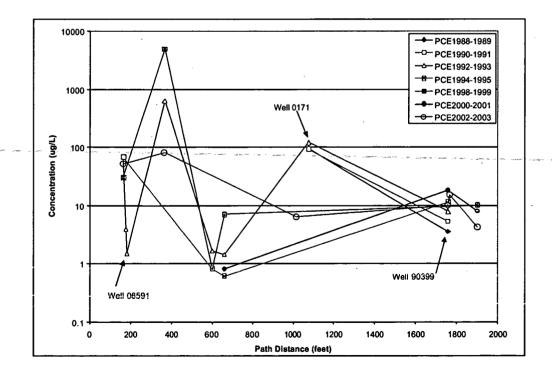


Figure 5-116 Response of PCE Concentrations vs Flowpath Distance in PSA2B, Various Periods



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### 5.1.10 Conceptual Model of Natural Attenuation and Biodegradation at the RFETS

A site-specific conceptual model has been developed for natural attenuation at the RFETS based on the generic conceptual model presented in Section 3. This model is also developed based on the evaluation and interpretations presented in this report. Because the emphasis of this evaluation is on interpreting geochemical data, geochemical processes are emphasized in the site-specific model. The relative importance of biodegradation is also discussed in relation to other natural attenuation processes. A summary of the important observations is provided below:

- Most of the CAH source areas are located in the IA where Site facilities and operations were
  conducted. Some remaining source areas are found east of the IA in the East Trenches area, on
  the hillsides south of the IA above Woman Creek, and north of the IA above Walnut Creek;
- CAH source areas at the RFETS are believed to be shallow, resulting from surface spills, leaking drums, shallow disposal trenches, or leaking subsurface storage tanks which were not deeply buried;
- All known CAH plumes at the Site occur in unconsolidated materials and weathered bedrock comprising the UHSU. In local areas, the subcropping, highly permeable No. 1 Sandstone of the Arapahoe Formation also constitutes a portion of the UHSU;
- Most CAH plumes in the IA are located within Rocky Flats Alluvium, although colluvial deposits
  may host plumes on the hill slopes above Woman and Walnut Creeks. Valley Fill Alluvium is
  only important where a plume may have reached stream alluvium along the creeks. For example,
  the East Trenches and Mound Site plumes appears to occur in Valley Fill Alluvium along Walnut
  Creek near Ponds B-1 and B-2;
- Groundwater within the UHSU is unconfined and the water table fluctuates seasonally:
- In the IA and vicinity, the UHSU water table is shallow, ranging from surface discharges at hillside seeps to more than 26 feet below grade. Typical depths to the water table during second quarter 2002 were approximately as follows:

Location	Water-Table Depth (ft bgs)
Western IA at Well P415989	8
Southwestern IA near B444 at Well 40499	. 14
Northern IA at Well 1986	3



Location	Water-Table Depth (ft bgs)		
Former Solar Evaporation Pond 207C at Well 00100	13		
Central IA near Sage Avenue Well 61399	. 5		
Eastern IA at Well 1987	9		
East Trenches at Well 11891	26		
Southeast IA at 904 Pad Well 0987	18		
Northeast of Pond C-1 at Well 90099	15		
Southern IA near B881 at Well 5287	9		

- Volatilization of CAHs may be significant where groundwater discharges at seeps above Walnut and Woman Creeks. Volatilization losses may also be expected for VC and CT where plumes are shallower than three feet;
- With respect to dilution, the RFETS has large areas of concrete and pavement that locally inhibit infiltration. However, periodic storm runoff to adjacent unlined ditches (such as the Central Avenue ditch) might produce local areas of groundwater recharge that may act to dilute a CAH plume and increase flow velocities;
- The predominant groundwater flow direction in the UHSU is generally eastwards. However, groundwater flow divides exist at the Site. Exceptions may occur locally where building drains, ditches, subsurface utility corridors, or large areas of paved surface may affect groundwater flow rates and direction;
- DO data indicate that shallow UHSU groundwater is generally well oxygenated, except in localized areas. The presence of DO at concentrations greater than 0.5 mg/L inhibits biodegradation. The average DO concentration in UHSU groundwater is 5.68 mg/L with a standard deviation of 2.48 mg/L;
- DO concentrations greater than a few mg/L in an aquifer low in TOC and anthropogenic carbon compounds (e.g., BTEX) does not support biodegradation by reductive dechlorination. This is called a Type III groundwater environment (Wiedemeier et al., 1999); and
- Microbial respiration and the potential presence of fuel hydrocarbons may cause rapid, but very localized depletion of DO within the CAH source areas. This may produce islands within the IA at IHSS 118.1, Mound, 903 Pad, or East Trenches where biodegradation locally takes place. Typically these islands are surrounded by a sea of oxidizing groundwater that can aerobically oxidize VC, but does not support reductive dechlorination.



Based on the above, it is hypothesized that the best site-specific conceptual model for biodegradation at RFETS is a combination of a Type I environment in the island source area surrounded by a Type III oxygenated environment. Figure 5-117 shows such a Site-specific conceptual model for RFETS. Comparison of the Type I (Figure 3-5) and III (Figure 5-117) conceptual models reveals some significant differences that are discussed below.

The most important natural attenuation mechanisms for PCE, TCE, and CT in a Type III oxygenated environment are sorption, advection, and dispersion. The lack of biodegradation in the Type III environment downgradient of the CAH source areas allows the PCE, TCE, and CT plumes (Figure 5-117) to migrate farther from the source than depicted on Figure 3-5. Differences between the Type I and III conceptual models include:

- Background and downgradient DO levels are higher in the Site-specific model (Figure 5-117);
- Although PCE and TCE have longer plumes, VC has a shorter, narrower plume because it can be aerobically oxidized by downgradient DO;
- Methane, acetate, and sulfide have smaller areas of stability within the plume because they can be oxidized downgradient or consumed by aerobic microbes;
- Redox zonation should be narrower (or tighter) around the Type I environment; and
- If Mn(IV) and Fe(III) reduction causes elevated concentrations of Mn(II) and Fe(II) in and below the source area, these metals may re-oxidize downgradient. Fe(II) will probably oxidize more rapidly, precipitating orange ferric oxyhydroxides in the downgradient porous medium and lowering the aqueous Fe(II) concentration. Dissolved concentrations of Mn(II) should also slowly decrease downgradient as oxidation to MnOOH or MnO<sub>2</sub> mineral phases takes place.



Type 3 Type 1 Туре 3 cis -1,2-DCE Redox а Concentration or Mass PCE Redox b cis-1,2-DCE NO<sub>3</sub> BOD Chloride SO<sub>4</sub> BOD (e.g., methanol) Concentration or Mass Chloride DO d NO<sub>3</sub> Back-Source Downgradient ground Distance Downgradient and Direction of Groundwater Flow

Figure 5-117 Site-Specific Conceptual Model of Biodegradation in Groundwater at RFETS

Adapted from Wiedemeier et al. (1999).



### 5.1.11 Site-Wide Natural Attenuation Summary

Biodegradation rates measured at the RFETS are at the low end of published biodegradation rates. Biodegradation at the RFETS can be viewed as occurring within small islands where anoxic conditions can be locally maintained to support reductive dechlorination CAHs like CT, PCE, and TCE. Fuel spills and detectable BTEX compounds spatially associated with some CAH sources provides an organic substrate for microbes and helps produce anoxic conditions through microbial respiration. Lathe coolant should be particularly amenable to biodegradation since the hydraulic oils provide a substrate for microbial growth and reductive dechlorination of the CAHs.

These islands of biodegradation are surrounded by a sea of oxidizing groundwater that does not support reductive dechlorination. The mean concentration of DO in groundwater at the RFETS is relatively high at 5.7 mg/L. Biodegradation is halted by these oxidizing conditions, although VC may be rapidly oxidized in DO-rich groundwater. Under oxidizing or reducing conditions, the solvent 1,1,1-TCA undergoes rapid hydrolysis (half-life 0.5 to 1.7 years) to acetic acid. Thus, of the primary solvents used at the RFETS, 1,1,1-TCA has the best chance for rapid attenuation. Chloroethane produced by either the TCA or TCE decay chains is also rapidly hydrolyzed (half-life 0.12 years) and is not expected to accumulate in the RFETS groundwater.

The following sections provide additional detail concerning biodegradation at each of the 7 PSAs evaluated.

#### 5.2 NATURAL ATTENUATION IN PSA2

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA2 (the 903 Pad Plume). In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.

#### 5.2.1 Biodegradation Screening

Wiedemeier scores were used to screen for biodegradation in individual wells. Wiedemeier scores were computed for groundwater from 95 monitoring wells located in PSA2. The maximum Wiedemeier scores at individual wells in PSA2 were generally low, ranging between -3 at well 4487 and 14 at well 11791. The average score for the wells in PSA2 was 3.4 with a standard deviation of 3.7. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation; and 6 to 14 points is limited evidence of biodegradation. Therefore, most PSA2 wells show no evidence or inadequate evidence of biodegradation. A few wells show limited evidence of biodegradation.



### 5.2.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA2 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

In PSA2 (Path A), TCE at well 06691 is predicted to have the longest plume duration and is expected to naturally attenuate to Tier II by 2106. The TCE decay half-life estimated at well 06691 is 23.7 years. CF at this well is predicted to attenuate to Tier II by 2029.

TCE well 1587 is predicted to naturally attenuate to Tier II by 2020. It has an estimated half-life of 6.3 years. PCE and CT at well 1587 are estimated to reach Tier II by 2026 and 2074, respectively.

### 5.2.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-9 summarizes the bulk attenuation rate constants ( $K_b$ ) and half-lives for PSA2.

Table 5-9 Bulk Attenuation Rate (Kb) and Half-Lives in PSA2

PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per yr)	Bulk Attenuation Half-Life (yr)	
2	1994-1995	1,1,1-TCA	0.026	26.7	
2	1992-1993	1,1,1-TCA	0.022	32.0	
2	1998-1999	1,1-DCA	0.004	162.7	
2	1992-1993	1,1-DCA	0.089	7.7	
2	2002-2003	1,1-DCE	0.083	8.3	
2	1998-1999	1,1-DCE ~	0.029	24.1	
2	1994-1995	1,1-DCE	0.138	5.0	
2	1992-1993 1,1-DCE 0.048		0.048	14.4	
2	2002-2003	CF	0.047	14.9	
2	1998-1999	CF	0.033	21.3	
2	1994-1995	CF	0.061	11.4	
2	1992-1993	CF	0.028	24.8	
2	2002-2003	cis-1,2-DCE	0.034	20.3	
2	2002-2003	СТ	0.044	15.8	



PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per yr)	Bulk Attenuation Half-Life (yr)
2	1998-1999	СТ	0.072	9.6
2	1994-1995	СТ	0.037	18.6
2	1992-1993	СТ	0.033	21.1
2	2000-2001	MC	0.232	3.0
2	1998-1999	MC	0.116	6.0
2	1994-1995	MC	0.154	4.5
2	1992-1993	MC	0.015	44.9
2	2002-2003	PCE	0.022	31.6
2	1998-1999	PCE	0.043	16.3
2	1994-1995	PCE	0.009	76.7
2	1992-1993	PCE	0.009	76.7
2	1998-1999	TCE	0.013	53.2
2	1994-1995	TCE	0.013	53.2

# 5.2.4 Biodegradation Rates in PSA2

Table 5-10 summarizes the biodegradation rate constants for PSA2.

Table 5-10 Biodegradation Rate Constants and Half-Lives in PSA2

PSA	Time Period	Constituent I Rate		Biodegradation Half-Life (years)
2	1994-1995	1,1,1-TCA	0.028	24.4
2	1992-1993	1,1,1-TCA	-0.023	29.7
2 -	1992-1993	1,1-DCA	0.099	7.0
2	1998-1999	1,1-DCA	0.004	161.8
2	1998-1999	PCE	0.050	13.9



### 5.2.5 Other Lines of Evidence of Biodegradation

Wells 00391 and 90299 in PSA2 have been noted to have sulfurous, swampy, or sewage odors. These olfactory indicators may suggest that groundwater at these wells is locally anoxic and biodegradation is occurring.

#### 5.2.6 Potential Contaminant Source Areas in PSA2

PSA2 is associated with the 903 Pad drum storage site. Potential source areas and CAH NAPLs were identified as follows:

- Historical documents were reviewed to identify known contaminant releases or NAPL occurrences at specific wells;
- Identification of NAPL samples or multi-phase groundwater samples in SWD;
- Identification of wells with the most elevated concentrations of parent solvents by inspection of plume maps for specific time periods; and
- Percent solubility calculations that suggest the presence of NAPLs.

NAPL occurrences were not identified in SWD for any of the PSA2 wells.

Historical analyses of CAH concentrations in groundwater from PSA2 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999).

Table 5-11 tabulates percent solubility statistics for PSA2 wells where the mean CAH concentrations in groundwater exceeded 1% of the solubility. Table 5-11 indicates that free phase parent solvents could potentially be present as DNAPLs near wells 06691, 0174, and 07391.

Table 5-11 Percent Solubility Statistics for CAHs in PSA2 Groundwater

САН	Well	Minimum % Solubility	Mean % Solubility	Maximum % Solubility	Standard Deviation % Solubility	Number of Data Records
CT	06691	0.01	4.44	12.42	4.16	19
PCE	0174	0.01	4.17	35.13	6.66	26
TCE	07391	0.00	6.37	20.00	4.44	50



#### 5.3 NATURAL ATTENUATION IN PSA3

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA3. In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.

### 5.3.1 Biodegradation Screening

PSA3 shares the same well coverage as PSA2. Therefore, the Wiedemeier scores are the same for both PSAs. PSA3 scores at individual wells were generally low, ranging between -3 at well 4487 and 14 at well 11791. Most PSA3 wells show no evidence or inadequate evidence of biodegradation. A few wells show limited evidence of biodegradation.

### 5.3.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA3 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed below since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

TCE in wells 07391 and 0271 are predicted to reach Tier II by 2284 and 2021, respectively. Well 07391 had an initial TCE concentration at time zero of 73,940  $\mu$ g/L. The natural attenuation TCE half-lives estimated at wells 07391 and 0271 are 21.1 and 34.8, respectively. CF in well 07391 is predicted to reach Tier II by 2078.

## 5.3.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-12 summarizes the bulk attenuation rate constants (K<sub>b</sub>) and half-lives for PSA3.

Table 5-12 Bulk Attenuation Rate Constants (Kb) and Half-Lives for PSA3

PSA	1 Time		_	Bulk Attenuation Half-Life (yr)	
3	1992-1993	1,1,1-TCA	0.248	2.8	
3	1992-1993	1,1-DCE	0.397	1.7	
3	2000-2001	MC	0.540	1.3	
3	2002-2003	TCE	0.495	1.4	



### 5.3.4 Biodegradation Rates in PSA3

The only biodegradation rate estimated in PSA3 is 0.99 per year for TCE during 2002-2003. The corresponding biodegradation half-life is 0.7 years.

### 5.3.5 Other Lines of Evidence of Biodegradation

Wells 00391 and 90299 in PSA2 have been noted to have sulfurous, swampy, or sewage odors. These olfactory indicators suggest that groundwater at these wells is locally anoxic and biodegradation is occurring.

#### 5.3.6 Potential Contaminant Source Areas in PSA3

Historical analyses of CAH concentrations in groundwater from PSA3 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999).

Table 5-13 tabulates percent solubility statistics for PSA3 wells where the mean CAH concentrations in groundwater exceeded 1% of the solubility. Table 5-13 indicates that free phase parent solvents could potentially be present as DNAPLs near wells 06691, 0174, and 07391.

Table 5-13 Percent Solubility Statistics for CAHs in PSA3 Groundwater

САН	Well	Minimum % Solubility	Mean % Solubility	Maximum % Solubility	Standard Deviation % Solubility	Number of Data Records
СТ	06691	0.01	4.44	12.42	4.16	19
PCE	0174	0.01	4.17	35.13	6.66	26
TCE	07391	0.00	6.37	20.00	4.44	50

#### 5.4 NATURAL ATTENUATION IN PSA5

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA5. In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.

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# 5.4.1 Biodegradation Screening

Wiedemeier scores were computed for groundwater from 37 monitoring wells in PSA5. The maximum Wiedemeier scores at individual wells in PSA5 were generally low, ranging between -3 at well 15199 and 10 at well 3586. The average score for the wells in PSA5 was 3.4 points with a standard deviation of 3.1. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation; and 6 to 14 points is limited evidence of biodegradation. Therefore, most PSA5 wells show no evidence or inadequate evidence of biodegradation.

# 5.4.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA5 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

TCE at well 0174 has a half-life of 19 years and is predicted to reach Tier II by 2161. MC in well 00897 had an initial concentration three times that of the TCE at well 0174, but has a short half-life of 1.1 years and is predicted to reach Tier II by 2009.

# 5.4.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-14 summarizes the bulk attenuation rates (K<sub>b</sub>) and half-lives for PSA5.

Table 5-14 Bulk Attenuation Rates (Kb) and Half-Lives in PSA5

PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
5	2002-2003	CF	1.505	0.5
5	1992-1993	CF	3.674	0.2
5	2002-2003	cis-1,2-DCE	1.710	0.4
5	2002-2003	MC	2.725	0.3
5	2000-2001	MC	2.899	0.2
5	1998-1999	MC	1.826	0.4
5	1990-1991	MC	0.029	23.9
5	2000-2001	PCE	1.193	0.6
5	1998-1999	PCE	0.727	1.0



PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
5	2002-2003	TCE	0.333	2.1
5	2000-2001	TCE	1.959	0.4
5	1986-1987	TCE	0.294	2.4

# 5.4.4 Biodegradation Rates in PSA5

Table 5-15 summarizes the biodegradation rates for PSA5.

Table 5-15 Biodegradation Rates in PSA5

PSA	Time Period	Constituent	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
5	1992-1993	CF	5.703	0.1
5	2002-2003	CF	1.845	0.4
5	1998-1999	МС	2.432	0.3

#### 5.4.5 Potential Contaminant Source Areas in PSA5

Historical analyses of CAH concentrations in groundwater from PSA5 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999).

Table 5-16 tabulates percent solubility statistics for PSA5 wells where the mean CAH concentrations in groundwater exceeded 1% of the solubility. Table 5-13 indicates that free phase parent solvents could potentially be present as PCE DNAPL near well 0174. This well is also located in PSAs 2 and 3.

Table 5-16 Percent Solubility Statistics for CAHs in PSA5 Groundwater

САН	Well	Minimum % Solubility	Mean % Solubility	Maximum % Solubility	Standard Deviation % Solubility	Number of Data Records
PCE	0174	0.01	4.17	35.13	6.66	26

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#### 5.5 NATURAL ATTENUATION IN PSA7

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA7. In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.

# 5.5.1 Biodegradation Screening

Wiedemeier scores were computed for groundwater from 65 monitoring wells in PSA7. The maximum Wiedemeier scores at individual wells in PSA7 were generally low, ranging between -1 at well 2487 and 12 at well 05691. The average score for wells in PSA7 was 4.0 points with a standard deviation of 3.4. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation; and 6 to 14 points is limited evidence of biodegradation. Therefore, most PSA7 wells show no evidence or inadequate evidence of biodegradation.

# 5.5.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA7 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

CT in well 12191 (Path A) is predicted to naturally attenuate to Tier II by 2243 based on a half-life of 47 years. CT and PCE in well 2587 is estimated to reach Tier II in 2186 and 2045, respectively.

#### 5.5.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-17 summarizes the bulk-attenuation rates (K<sub>b</sub>) and half-lives for PSA7.

Table 5-17 Bulk Attenuation Rates (Kb) and Half-Lives in PSA7

PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
7	1996-1997	1,1,1-TCA	0.030	22.8
7	1994-1995	1,1,1-TCA	0.589	i.2
7	1990-1991	1,1,1-TCA	0.294	2.4
7	2002-2003	1,1-DCE	0.405	1.7



PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
7	1996-1997	1,1-DCE	0.202	3.4
7	1994-1995	1,1-DCE	0.225	3.1
7	1990-1991	1,1-DCE	1.215	0.6
7	1994-1995	CF	0.557	1.2
7	2002-2003	cis-1,2-DCE	0.427	1.6
7	1994-1995	cis-1,2-DCE	0.453	1.5
7	1992-1993	cis-1,2-DCE	0.507	1.4
7	1990-1991	cis-1,2-DCE	0.400	1.7
7	1996-1997	СТ	0.400	1.7
7	1994-1995	СТ	0.338	2.0
7	1990-1991	СТ	0.138	5.0
7	1994-1995	MC	0.651	1.1
7	1990-1991	MC	0.217	3.2
7	2002-2003	PCE	0.209	3.3
7	1994-1995	PCE	0.200	3.5
7	1992-1993	PCE	0.100	6.9
7	1990-1991	PCE	0.054	12.7
7	2002-2003	TCE	0.458	1.5
7	1994-1995	TCE	0.073	9.5
7	1992-1993	TCE	0.238	2.9
7	1990-1991	TCE	0.055	12.6

# 5.5.4 Biodegradation Rates in PSA7

Table 5-18 summarizes the biodegradation rates for PSA7.

Table 5-18 Biodegradation Rates in PSA7

PSA	Time Period	Constituent	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
7	1994-1995	1,1,1-TCA	0.768	0.9
7	1990-1991	1,1,1-TCA	0.339	2.0
7	1996-1997	1,1,1-TCA	0.031	22.4
7	1990-1991	1,1-DCE	1.560	• 0.4
7	2002-2003	1,1-DCE	0.443	1.6
7	1996-1997	1,1-DCE	0.212	3.3



PSA	Time Period	Constituent	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
7	2002-2003	cis-1,2-DCE	0.463	1.5
7	1990-1991	cis-1,2-DCE	0.432	1.6
7	1994-1995	MC	0.733	0.9
7	1990-1991	MC	0.226	3.1
7	2002-2003	TCE	0.518	1.3

# 5.5.5 Potential Contaminant Source Areas in PSA7

Historical analyses of CAH concentrations in groundwater from PSA7 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999).

Table 5-19 tabulates percent solubility statistics for PSA7 wells where the mean CAH concentrations in groundwater exceeded 1% of the solubility. Table 5-19 indicates that free phase parent solvents could potentially be present as TCE DNAPL near wells 3687, 20891, and 20991.

Table 5-19 Percent Solubility Statistics for CAHs in PSA7 Groundwater

САН	Well	Minimum % Solubility	Mean % Solubility	Maximum % Solubility	Standard Deviation % Solubility	Number of Data Records
TCE	20891	1.92	1.92	1.92		1
TCE	20991	2.63	2.63	2.63		1
TCE	3687	0.00	2.75	20.17	3.55	69

#### 5.6 NATURAL ATTENUATION IN PSA10

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA10. In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.



# 5.6.1 Biodegradation Screening

Wiedemeier scores were computed for groundwater from 76 monitoring wells located in PSA10. The maximum Wiedemeier scores at individual wells in PSA10 were generally low, ranging between -3 at well 59294 and 10 at well 6886. The average score for wells in PSA10 was 3.2 points with a standard deviation of 2.7. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation; and 6 to 14 points is limited evidence of biodegradation. Most PSA10 wells show no evidence or inadequate evidence of biodegradation.

# 5.6.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA10 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

PCE in well P416889 is predicted to naturally attenuate to Tier II by 2193 based on a half-life of 63 years. PCE and TCE in well 41299 appears to attenuate much faster and is predicted to naturally attenuate to Tier II by 2016 and 2008, respectively.

# 5.6.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-20 summarizes the bulk attenuation rates (K<sub>b</sub>) and half-lives for PSA10.

Table 5-20 Bulk Attenuation Rates (K<sub>b</sub>) and Half-Lives in PSA10

PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
10	2002-2003	cis-1,2-DCE	0.024	29.0
10	2000-2001	МС	0.033	20.9
10	2002-2003	PCE	0.003	234.0
10	2000-2001	PCE	0.004	156.0
10	1996-1997	TCE	0.010	66.2

#### 5.6.4 Biodegradation Rates in PSA10

Table 5-21 summarizes the biodegradation rates and half-lives for PSA10.



Table 5-21 Biodegradation Rates and Half-Lives in PSA10

PSA	Time Period	Constituent	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
10	2002-2003	cis-1,2-DCE	0.025	27.4
10	2000-2001	MC	0.036	19.4
10	1996-1997	TCE	0.011	63.9

#### 5.6.5 Other Lines of Evidence of Biodegradation

PSA10 wells 21097, 58194, 58594, 59393, 62793, and 62893 have been noted to have sulfurous, swampy, or sewage odors. These olfactory indicators may suggest that groundwater at these wells is locally anoxic and biodegradation is occurring.

#### 5.6.6 Potential Contaminant Source Areas in PSA10

Historical analyses of CAH concentrations in groundwater from PSA10 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999). None of the mean concentrations of CAHs in PSA10 exceeded 1% solubility.

#### 5.7 NATURAL ATTENUATION IN PSA12

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA12. In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.

#### 5.7.1 Biodegradation Screening

Wiedemeier scores were computed for groundwater from 54 monitoring wells in PSA12. The maximum Wiedemeier scores at individual wells in PSA12 were generally low, ranging between -3 at well 21398 and 19 at well 1986. The average score for wells in PSA12 was 3.2 points with a standard deviation of 3.7. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation; and 6 to 14 points is limited evidence of biodegradation. Most of the wells in PSA12 show no or inadequate evidence of biodegradation. However, well 1986 (19 points) has adequate



evidence of biodegradation. Wells P115589 and P115689 (9 points) show limited evidence of biodegradation.

# 5.7.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA12 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

The longest predicted attenuation period in PSA12 is for TCE at well 21598. TCE is predicted to naturally attenuate to Tier II by 2076 based on a half-life of 19 years. CT in well 21298 is predicted to naturally attenuate to Tier II by 2071 based on a half-life of 63. PCE is predicted to be rapidly attenuated at well 84702 reaching Tier II by 2005 based on a half-life of 0.5 years.

# 5.7.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-22 summarizes the bulk attenuate rates (K<sub>b</sub>) and half-lives for PSA12.

Table 5-22 Bulk Attenuation Rates and Half-Lives in PSA12

PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
12	2002-2003	1,1-DCA	0.543	1.3
· 12	1998-1999	1,1-DCA	0.724	1.0
12	2002-2003	1,1-DCE	0.187	3.7
12	1998-1999	1,1-DCE	0.034	20.4
12	1998-1999	cis=1,2=DCE	1:048	0.7
12	2002-2003	MC	0.041	16.9
12	1998-1999	MC	0.389	1.8
12	2002-2003	PCE	0.007	101.1
12	1998-1999	PCE	0.117	5.9
12	1998-1999	TCE	0.152	4.5
12	2002-2003	VC	1.983	0.3



# 5.7.4 Biodegradation Rates in PSA12

Table 5-23 summarizes the biodegradation rates and half-lives for PSA12.

Table 5-23 Biodegradation Rates in PSA12

PSA	Time Period	Constituent	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
12	1998-1999	1,1-DCA	0.846	0.8
12	2002-2003	1,1-DCA	0.612	1.1
12	1998-1999	cis-1,2-DCE	1.335	0.5
12	. 2002-2003	MC	0.041	16.7

#### 5.7.5 Other Lines of Evidence of Biodegradation

PSA12 wells 21698, 21998, and 84602 have been noted to have sulfurous, swampy, or sewage odors. These olfactory indicators may suggest that groundwater at these wells is locally anoxic and biodegradation is occurring.

#### 5.7.6 Potential Contaminant Source Areas in PSA12

Historical analyses of CAH concentrations in groundwater from PSA12 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999).

Table 5-24 tabulates percent solubility statistics for PSA 12 wells where the mean CAH concentrations in groundwater exceeded 1% of the solubility. Table 5-24 indicates that free phase parent solvents could potentially be present as CT DNAPL near wells 5670.

Table 5-24 Percent Solubility Statistics for CAHs in PSA12 Groundwater

САН	Well	Minimum % Solubility	Mean % Solubility	Maximum % Solubility	Standard Deviation % Solubility	Number of Data Records
Carbon Tetrachloride	5670	1.09	1.09	1.09		1



#### 5.8 NATURAL ATTENUATION IN PSA14

This section presents data interpretations describing the location and extent of natural attenuation processes in groundwater beneath PSA14. In particular, biodegradation is discussed if sufficient data were available to interpret its occurrence.

# 5.8.1 Biodegradation Screening

Wiedemeier scores were computed for groundwater from 54 monitoring wells in PSA12. The maximum Wiedemeier scores at individual wells in PSA12 were generally low, ranging between -3 at well 21398 and 19 at well 1986. The average score for wells in PSA12 was 3.2 points with a standard deviation of 3.7. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation, and 6 to 14 points is limited evidence of biodegradation. Most of the wells in PSA12 show no or inadequate evidence of biodegradation. However, well 1986 (19 points) has adequate evidence of biodegradation. Wells P115589 and P115689 (9 points) show limited evidence of biodegradation.

Wiedemeier scores were computed for groundwater from 54 monitoring wells in PSA14. The maximum Wiedemeier score at individual wells in PSA14 were generally low, ranging between -3 at well 30002 and 19 at well 1986. The average score for the wells in PSA14 was 3.9 points with a standard deviation of 4.5. Scores less than 1 indicate no evidence of biodegradation; 1 to 5 points is inadequate evidence of biodegradation; and 6 to 14 points is limited evidence of biodegradation. Most PSA14 wells show no evidence or inadequate evidence of biodegradation. Well 1986 (19 points) has adequate evidence of biodegradation. Well 18599 (14 points) shows limited evidence of biodegradation.

After well 33502 (PSA13), well 1986 has the second highest Wiedemeier score (19) at the RFETS and shows adequate evidence of biodegradation. Well 1986 groundwater has elevated mean concentrations of ferrous and total iron at 26.8 and 29.9 mg/L, respectively. Low levels of dissolved sulfide were detected in the well at a concentration of 3 µg/L. The mean ORP reading in this well is -115 mV at a near-neutral pH of 6.88. Finally, the average DO content of this groundwater is low (1.6 mg/L). In particular, the low-ORP in combination with elevated Fe(II) and detectable sulfide suggest that the groundwater is capable of reducing sulfate and Fe(III). This is a suitable environment for biodegradation via reductive dechlorination.

# 5.8.2 Point Attenuation Rate Constants from Natural Log C Versus Time Plots

Point attenuation rates were computed for wells in PSA14 and were used to estimate the amount of time required for CAHs to naturally attenuate. Wells exhibiting the slowest attenuation rates are discussed



since the overall plume is not considered to have attenuated until all contaminants have reached their Tier II groundwater action levels.

CF at well 18799 is predicted to naturally attenuate to Tier II by 2455 based on a half-life of 190 years. It has the longest predicted attenuation rate in PSA14. PCE at well 18499 is estimated to naturally attenuate to Tier II by 2042, at a half-life of 10 years.

# 5.8.3 Bulk Attenuation Rate Constants from Natural Log C Versus Distance Plots

Table 5-25 summarizes the bulk attenuation rates  $(K_b)$  and half-lives for PSA14.

Table 5-25 Bulk Attenuation Rates (Kb) and Half-Lives in PSA14

PSA	Time Period	Constituent	Bulk Attenuation Rate K <sub>b</sub> (per year)	Bulk Attenuation Half-Life (years)
14	2000-2001	1,1-DCA	0.087	7.9
14	1998-1999	1,1-DCA	0.139	5.0
14	1998-1999	1,1-DCE	0.086	8.0
14	2002-2003	CF	0.243	2.9
14	2000-2001	CF	0.291	2.4
14	1998-1999	CF	0.160	4.3
14	1998-1999	cis-1,2-DCE	0.032	21.8
14	2002-2003	СТ	0.145	4.8
14	2000-2001	СТ	0.065	10.6
14	1998-1999	СТ	0.126	5.5
14	2002-2003	MC	0.165	4.2
14	2000-2001	MC.	0.086	8.0
14	1998-1999	МС	0.155	4.5
14	2002-2003	PCE	0.075	9.3
14	2000-2001	PCE	0.069	10.1
14	1998-1999	PCE	0.087	8.0
14	2002-2003	TCE	0.019	35.7
14	2000-2001	TCE	0.053	13.0
14	1998-1999	TCE	0.102	6.8



# 5.8.4 Biodegradation Rates in PSA14

Table 5-26 summarizes the biodegradation rates and half-lives for PSA14.

Table 5-26 Biodegradation Rates and Half-Lives in PSA14

PSA	Time Period	Constituent	Biodegradation Rate (per year)	Biodegradation Half-Life (years)
14	1998-1999	1,1-DCA	0.164	4.2
14	2000-2001	1,1-DCA	0.097	7.1
14	1998-1999	1,1-DCE	0.100	7.0
14	2000-2001	CF	0.393	1.8
14	1998-1999	cis-1,2-DCE	0.033	20.8
14	2000-2001	PCE	0.089	7.8
14	2000-2001	TCE	0.060	11.6
14	2002-2003	TCE	0.020	34.2

# 5.8.5 Other Lines of Evidence of Biodegradation

PSA14 wells 20398, 20498, 20798, 20998, and 21698 have been noted to have sulfurous, swampy, or sewage odors. These olfactory indicators may suggest that groundwater at these wells is locally anoxic and biodegradation is occurring.

#### 5.8.6 Potential Contaminant Source Areas in PSA14

Table 5-27 was compiled from the results of a search of the SWD database for potential NAPL samples. These samples are believed to represent various NAPL portions and groundwater. Analytical data for these mixed-media samples are not representative of Site groundwater quality and were not used to calculate rate constants or are depicted on graphs.

Although no reports of fuel releases have been found, No. 2 diesel fuel was detected in TPH analyses of NAPL samples from PSA14 during 1997 (RMRS, 1997). Table 5-27 indicates that up to 3,200 mg/L of TPH was found as a possible LNAPL floating on groundwater and DNAPL in one or more wells.

PSA14 wells known or suspected to contain CT DNAPLs include 05197, 05397, 05497, 05897, 05997, and 18599. Substantial concentrations of CF and MC are associated with the CT, and the presence of

these daughter products suggests that biodegradation is taking place (Table 5-27). The No.2 diesel fuel is probably helping to lower the Eh and provides a carbon source for reductive dechlorination.

Table 5-27 Mixed-Media NAPL and Groundwater Samples Collected from Wells in PSA14

Well	Sample Number	Sample Medium <sup>l</sup>	Collection Date	TPH as No.2 Diesel (mg/L)	Carbon Tetrachloride (mg/L)	Chloroform (mg/L)	Methylene Chloride (mg/L)
05197	GW10016RM	Silty water with some NAPL droplets	9/26/1997	<6.2	240	35	2.3
05397	GW10019RM	Water with thin LNAPL slick	9/26/1997	<6.2	680	26	25
05397	GW10022RM	40% DNAPL, and potential LNAPL	9/26/1997	1700	120000	<5000	<5000
05497	GW06305TE	Probably water and DNAPL	3/8/1999		690000		
05497	GW10018RM	Pure DNAPL in VOC sample	9/26/1997	3100	180000	2700	2500
05497	GW10023RM	Mostly water with 10% DNAPL and possibly LNAPL	9/26/1997	3200	1100	<5000	180
05497	GW10026RM	Pure DNAPL in VOC sample	9/26/1997	3200	130000	<5000	3600
05897	GW10020RM	Probably water and DNAPL	9/26/1997		250000		
05897	GW10025RM	DNAPL	9/26/1997	2600	250000	3800	2600
05997	GW10021RM	Pure DNAPL	9/26/1997	2600	240000	3600	<5000
05997	GW10024RM	20-25% DNAPL, rest water	9/26/1997	2700	880	160	13
18599	GW06289TE	DNAPL	3/2/1999		:		

<sup>&</sup>lt;sup>1</sup> Sample medium description based on EVENT\_COMMENT in SWD and RMRS (1997) Pre-Remedial Investigation of IHSS 118.1 Summary Report

Historical analyses of CAH concentrations in groundwater from PSA14 were retrieved from SWD, the percent solubility calculated, and compared against the published solubility of each compound in pure water. A commonly used rule of thumb is that CAH solubilities greater than 1% may indicate the presence of a nearby NAPL source area at or immediately upgradient of the well (Brady et al., 1999).

Table 5-28 tabulates percent solubility statistics for PSA14 wells where the mean CAH concentrations in groundwater exceeded 1% of the solubility. Table 5-28 indicates that free phase parent solvents could potentially be present CT DNAPL in PSA 14 (IHSS 118.1) and 1,1,1-TCA DNAPL near well 18399.

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Table 5-28 Percent Solubility Statistics for CAHs in PSA14 Groundwater

САН	Well	Minimum % Solubility	Mean % Solubility	Maximum % Solubility	Standard Deviation % Solubility	Number of Data Records
СТ	18199	0.25	2.98	4.84	1.06	24
1,1,1-TCA	18399	6.34	6.34	6.34		1
СТ	18399	1.37	3.62	6.83	1.89	9
СТ	18499	1.19	3.04	7.18	1.64	13
СТ	18599	0.13	2.39	4.97	2.16	7
СТ	5670	1.09	1.09	1.09		1

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#### 6 CONCLUSIONS

The natural attenuation rates of CAHs in groundwater at the RFETS have been evaluated using lines of evidence suggested in the published literature. These lines of evidence include estimation of biodegradation rate constants, bulk attenuation rate constants, point attenuation rate constants, and overall mass removal of CAHs from groundwater.

Several hundred two-dimensional charts were prepared to:

- Estimate attenuation rate constants;
- Identify redox environments that support biodegradation;
- Visualize the extent of natural attenuation of CAHs over time; and
- Interpret the attenuation of CAH concentrations with groundwater migration distance along a contaminant plume flowpath.

An additional line of evidence was developed through the construction of isopleth maps of CAH plume extents during two-year time periods for the 18 years of groundwater monitoring data currently available. Three different sets of isopleth maps were created to meet different objectives.

- Detects and Nondetects These maps were designed to show all of the available data and areal
  extent of CAHs for each time period by plotting detected concentrations to the lowest reporting
  limit. They also indicate data below the reporting limit where wells contained groundwater
  lacking detectable concentrations of CAHs;
- Tier II Plume Maps Plumes were defined in this report as areas where aqueous CAH
  concentrations exceeded Tier II groundwater action levels. These maps show Tier II
  concentrations and greater. Only well control is shown below Tier II. To facilitate comparing
  parent CAH plumes between time periods, all the maps a common set of contour intervals
  depending on the CAH; and
- Tier I Plume Maps Only 6 CAHs were found to have plumes with concentrations greater than Tier I groundwater action levels during 2002-2003. Maps were included for Tier I plumes because they may require further evaluation for potential remedial actions. Other than natural attenuation, remedial actions were not evaluated in this report..

The above three sets of isopleth maps were discussed in Section 5. Many other isopleth maps are provided in Appendix F. The 6 Tier I CAH plumes presently existing in groundwater at RFETS include CT, CF, PCE, TCE, 1,1-DCE, and VC.



Wiedemeier scores were used as a screening tool to quickly assess the extent of biodegradation at the Site. This screening system is based on the concept that biodegradation will cause predictable changes in groundwater chemistry (EPA, 1998). If most of the relevant water quality parameters are measured, then their concentrations may be scored using this system and assign points to each parameter at each well. The total number of points produce a Wiedemeier score for each well.

The available field and laboratory analyses at each well were scored under the Wiedemeier system. Wiedemeier scores for 579 monitoring wells at the RFETS ranged from a minimum of -3 points to a maximum of +22 points. These data had a mean of 3 points and a standard deviation of 3.4 points. The mean plus two standard deviations (M2SD) Wiedemeier score was 9.82. Cumulative frequency data indicate that about 99.2% of wells at the RFETS have Wiedemeier scores <15 points indicating less than adequate evidence of biodegradation.

Based on presently available data, well 33502 is the only well at the RFETS with strong evidence of biodegradation based on the Wiedemeier scores. Well 33502 had a maximum score of 22. Well 33502 is located in PSA13 beneath Sage Avenue, just north of B-335. Well 33502 groundwater contains elevated VC concentrations (e.g., 1,200  $\mu$ g/L in February 2003). Potential indicators of biodegradation at well 33502 include elevated mean concentrations of ferrous iron (22 mg/L), total iron (30 mg/L), low ORP (-154 mV) at field pH 6.95, and detectable sulfide (20  $\mu$ g/L). DO concentrations in groundwater at well 33502 are relatively low for the RFETS groundwater, averaging 1.6 mg/L.

Only one other well, well 1986, had adequate evidence of biodegradation with a maximum Wiedemeier score of 19. Well 1986 is located in PSA14 about 1500 feet northeast of well 33502. Well 1986 appears to be located in the original drainage west of B-771. All other wells had Wiedemeier scores of 14 points or less:

- 125 wells fell in the limited evidence of biodegradation category (6 to 14 points);
- 349 wells had inadequate evidence of biodegradation (1 to 5 points); and
- Hundreds of other wells and drains showed no positive evidence of biodegradation.

Approximately 170 charts were prepared by plotting ln C versus D using data from wells located along a flowpath in each PSA. Each chart shows the trend in detected concentrations of a single CAH in groundwater at multiple wells located along a flowpath for a limited time interval

These plots were prepared to determine  $K_b$  values for individual CAHs in each of 7 PSAs of interest during periods with sufficient analytical data.  $K_b$  values constants are useful for two purposes. They can be used to predict the future extent, or size of a plume, and whether it should grow, shrink, or remain at steady-state. Second, the slopes that are used to compute  $K_b$  values can be used to estimate biodegradation rate constants for steady-state plumes.



Generally, natural attenuation processes reduce contaminant concentrations during groundwater migration along a flowpath from a contaminant source area. One hundred and three of the ln C-vs-D plots exhibited regression lines with negative slopes (positive  $K_b$  rates) indicating that the concentrations of CAHs were naturally attenuated during contaminant migration. However, another 64 of the ln C-vs-D plots had positive slopes (negative  $K_b$  rates) indicating that the concentrations of some contaminants were actually increasing through time in groundwater at the RFETS.

K<sub>b</sub> values were used to predict the amount of time required for a CAH to degrade to the Tier II groundwater action level. A wide range of predicted decay times were found for the CAHs evaluated Positive degradation times ranged from one to more than 1,200 years to attenuate to Tier II.

When  $K_b$  values were used to predict if plumes would grow or shrink, the data indicated that most plumes at the RFETS would grow. Sixty-one results (Table 5-4) indicated that plumes would grow, while 35 were predicted to remain steady (within 25% of length). Only 7 of the plumes were predicted to shrink.

Plumes that were predicted to shrink appear to be attenuating faster, at an average  $K_b$  half-life of 7.5 years. Plumes predicted to grow were attenuating slower, with average  $K_b$  half-lives of 19.8 years. The half-life of steady-state plumes averaged 15.1 years.

Grouping the bulk attenuation rates by CAH yielded positive  $K_b$  values for 10 CAHs. Arranged from highest to lowest average  $K_b$  rate per year, these CAHs (and their  $K_b$  value) included VC (1.98), CF (0.66), MC (0.60), cis-1,2-DCE (0.51), TCE (0.28), 1,1-DCA (0.26), 1,1-DCE (0.25), 1,1,1-TCA (0.20), PCE (0.17), CT (0.14).

In summary, 62% of the ln C-vs-D plots had negative slopes and positive bulk attenuation rate constants, indicating that natural attenuation processes are lowering CAH concentrations in groundwater at the RFETS. However, 38% of the ln C-vs-D plots indicated that CAHs were locally increasing in concentration faster than they could be destroyed by biodegradation or hydrolysis or otherwise naturally attenuated through sorption, volatilization, dilution, and dispersion. The most likely explanation is that the plotted plume segments with positive slopes show only the rising limb of increasing daughter product concentrations. If additional groundwater monitoring data were available along the full length of the CAH plume flowpaths, then the daughter concentrations would peak and attenuate with distance in accordance with the conceptual model Figure 3-5.

Biodegradation rates were computed for the attenuation of CAHs in groundwater at the RFETS. This was done using the 1D method of Buscheck and Alcantar (1995), recognizing that this method likely overestimates the true biodegradation rate (Zhang and Heathcote, 2003). Lack of data concerning the dimensions and exact location of contaminant source areas precluded the application of more sophisticated methods.



The 1D method requires that the plume is at steady-state during the time period, otherwise the computed rate constant will be an approximation of the biodegradation rate. Thirty-five biodegradation rate constants were computed for plumes of individual CAHs which were predicted to remain at steady-state. A summary of biodegradation rates is provided in Table 6-1.

Table 6-1 Biodegradation Rate Statistics for CAHs in UHSU Groundwater

САН	Minimum Biodegradation Rate (per year)	Mean Biodegradation Rate (per year)	Maximum Biodegradation Rate (per year)	Sample Standard Deviation	Number of Rate Measurements
PCE	0.050	0.069	0.089	0.028	2
TCE	0.011	0.320	0.990	0.431	5
cis-1,2-DCE	0.025	0.457	1.33	0.533	5
1,1,1-TCA	0.023	0.238	0.768	0.326	5
1,1-DCA	0.004	0.304	0.846	0.341	6
1,1-DCE	0.100	0.579	1.56	0.670	4
CF	0.393	2.65	5.70	2.74	3
MC	. 0.036	0.694	2.43	1.01	5

Table 6-1 does not include a biodegradation rate for CT because none of the CT plumes were considered to be at steady-state. However, an approximate biodegradation rate can be estimated by averaging the rates for 10 non-steady-state CT plumes. This estimated CT biodegradation rate is 0.163 per year.

CF has the highest mean degradation rate at 2.65 per year and its daughter MC has the second highest mean of 0.694 per year. These CAHs also have the greatest maximum degradation rates. The slowest mean rates are for the parent solvents PCE at 0.07 per year, TCE at 0.32 per year, and 1,1,1-TCA at 0.24 per year.

Biodegradation mean half-lives for CAH compounds in groundwater at the RFETS are 1,1,1-TCA at 15.9 years; 1,1-DCA at 30.3 years; 1,1-DCE at 3.0 years; CF at 0.8 years; cis-1,2-DCE at 10.4 years; MC 8.1 at years; PCE at 10.8 years; and TCE at 22.4 years.

The biodegradation rates at the RFETS were compared with those for other chlorinated solvent sites. Biodegradation rate statistics were compiled from published field and laboratory biodegradation rate investigations (Aronson and Howard, 1997). All of the mean biodegradation rates at the RFETS are less than 1.0, except for CF at 2.65 per year. The mean biodegradation rates for non-RFETS sites are much faster. For example, the non-RFETS CF mean biodegradation rate is 29.2 per year which is 11 times faster than biodegradation rates determined for the RFETS. The non-RFETS PCE mean biodegradation rate is 9.86, about 143 times faster than the mean rate at the RFETS. The non-RFETS TCE mean



biodegradation rate is 4.02, about 12 times faster than the mean rate at the RFETS. Assuming that 1,2-DCA decays at a similar rate to 1,1-DCA, then the non-RFETS mean biodegradation rate is 2.78, about 9 times faster than 1,1-DCA decays at the RFETS. Comparison of the estimated mean CT biodegradation rate (0.163 per year) at the RFETS to the non-RFETS mean of 124 per year indicates that the non-RFETS mean biodegradation rate is 760 times faster than CT biodegradation at the RFETS.

In conclusion, biodegradation rates for CAHs in groundwater at the RFETS are at or near the low end of published biodegradation rate constants. Biodegradation rate constants computed from the 1D method of Buscheck and Alcantar (1995) are believed to overestimate the true rate constant by up to 65% in comparison to a more rigorous 3D method (Zhang and Heathcote, 2003). Thus, the true biodegradation rates at RFETS are likely to be even slower. These slow degradation rates would make it difficult to demonstrate that MNA is a practical groundwater remedial option for CAH-contaminated groundwater at the RFETS.

Concentration versus time rate constants, also called point attenuation rate constants describe the attenuation of a CAH plume at a single monitoring well. At most industrial sites with CAH plumes, the rate of weathering and attenuation of the DNAPLs in the source area is slower than the rate of attenuation of dissolved CAHs. In this case, the life-cycle of the groundwater plume is controlled by the rate of attenuation at the source and can be predicted by point attenuation rates measured for the most contaminated wells (Newell et al., 2002).

These rate constants are based on the slope of a plot of ln C of a CAH versus T. The present investigation constructed 282 plots of ln C-vs-T. Declining or attenuating contaminant concentrations through time are indicated by negative slopes when regression lines are fitted to the plots. Most of the plots (168) exhibited negative slopes, while 114 had regression lines with positive slopes, indicating CAH concentrations that are not being attenuated.

Point attenuation rates were computed for wells in the 7 PSAs. These rates were used to estimate the time required for natural attenuation of the CAH plumes. Attenuation rates vary by chemical. The slowest rates are of interest because the overall plume is not remediated until all contaminants have reached their attenuation goals (i.e., Tier II).

In PSA2 (path A) the longest plume duration for which data are available occurs at well 06691. The TCE plume at this well is expected to naturally attenuate to Tier II by the year 2106. The TCE decay half-life is estimated at approximately 24 years at well 06691. The CF plume at this well is predicted to achieve Tier II by 2029.

The TCE plume at PSA2 well 1587 has a shorter half-life of 6.3 years and is predicated to reach Tier II by 2020. PCE at well 1587 is predicted to reach Tier II during 2026. CT in groundwater at well 1587 is predicted to reach Tier II by 2074.



Well 07391 (PSA3 path A) had a large concentration of TCE (73,940 µg/L) at time zero. At a natural attenuation half-life of 21.1 years, TCE in this well is predicted to reach Tier II in 2284. However TCE at well 0271 has a 34.8 year half-life and is predicted to reach Tier II by 2021. Chloroform in well 07391 is predicted to reach Tier II by 2078.

The longest identified attenuation period in PSA5A is predicted to meet Tier II by 2161 for TCE at well 0174 which has an estimated half-life of 19 years. Interestingly, MC in well 00897 had an initial concentration three times that of the TCE at well 0174, but it has a short half-life of about 1.1 years and is predicated to reach Tier II by 2009.

Well 12191(PSA7) has the longest predicted attenuation period in that PSA. CT in well 12191, with a half-life of 47 years, is predicted to attenuate to Tier II by 2243. CT and PCE in well 2587 is predicted to reach Tier II by 2186 and 2045, respectively.

PCE concentrations in well P416889 attenuate with a half-life of 63 years, yielding the longest predicted attenuation period for PSA10. The PCE should attenuate by the year 2193. PCE in well 41299 groundwater is predicted to attenuate much more rapidly, reaching Tier II by 2016. TCE in well 41299 is predicted to reach Tier II by 2008.

The longest predicted attenuation period in PSA12 is at well 21598 for TCE, which reaches Tier II in the year 2076. The TCE half-life at this well is 19 years. A lower initial concentration of CT is predicted to reach Tier II in well 21298 in 2071. The CT half-life is at this well is 63 years. PCE rapidly attenuates (half-life 0.5 years) in well 84702 and is predicted to reach Tier II in 2005.

One of the longest predicted attenuation rates is for CF in well 18799 in PSA14. Chloroform in this well has a half-life of about 190 years and is predicted to reach Tier II in about 2455. PCE concentrations in groundwater at well 18499 is predicted to attenuate to Tier II in about 2042 at a half-life of 10 years.

If all of the half-lives for positive point attenuation rate constants are grouped together by CAH some interesting statistics emerge. There is only one rate measurement for chloroethane, but it has the shortest half-life (0.7 years) of the RFETS CAHs. Published literature indicates that chloroethane has a hydrolysis half-life of 0.12 years, so these values are in reasonable agreement. Of the parent solvents, the literature indicates that 1,1,1-TCA has a relatively short hydrolysis half-life of 0.5 to 2.5 years. In the RFETS groundwater, its mean half-life is comparable at 5 years. TCE is the longest-lived parent CAH with a half-life of 27 years, while CT is second at 18 years, and PCE is third at 14 years.

Another line of evidence demonstrating natural attenuation of the RFETS CAH groundwater plumes is decreases in CAH mass over time. If natural attenuation is occurring large decreases in CAH mass would be observed during the more recent period. The mean concentrations of individual CAH compounds in groundwater were computed for individual wells during two periods 1992-1993 and 2002-2003, a

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separation of 10 years. The CAH concentrations in groundwater were converted from  $\mu g/L$  to micromoles/liter ( $\mu$ Mole/L). If the number of  $\mu$ Moles decrease between the two periods a net loss of CAHs through natural attenuation has occurred. At each well the  $\mu$ Moles of all detected CAH compounds were summed to estimate total  $\mu$ Moles of chlorinated aliphatics per liter during the period. A database query identified 122 wells with CAH analytical data for both periods.

The total mass of CAHs decreased between the two periods (1992-1993 and 2002-2003) at 91 monitoring wells indicating that natural attenuation has occurred at those wells. The average decrease in mass at these wells was 14.1  $\mu$ Moles per liter per well. The remaining 31 wells showed no evidence of attenuation, but showed an increase in CAH mass. The average mass increase was relatively small at 3.5  $\mu$ Moles per liter per well. If the changes in mass at all 122 wells are summed, the overall net change is a mass loss of 1,169  $\mu$ Moles per 122 liters, or 9.6  $\mu$ Moles per liter at an average well. This mass loss provides evidence that CAH plumes at the RFETS are undergoing natural attenuation. The overall decline is actually a rate, 9.6  $\mu$ Moles/ liter/ decade at each well. The site-wide average CAH molar attenuation rate is 0.96  $\mu$ Mole/ liter/ year.

The ratios of the cis and trans stereoisomers of 1,2-DCE (i.e., cis-1,2-DCE and trans-1,2-DCE) have been used as an indicator of biodegradation. DCE is generally a mixture of cis- and trans-1,2-DCE. In contrast, biodegradation produces mainly cis-1,2-DCE (EPA, 1998). The cis/trans 1,2-DCE ratio is typically greater than 25 to 1 in groundwater where biodegradation is actively proceeding. The cis/trans 1,2-DCE ratio was computed for each well and sampling event with detectable concentrations for both isomers. Although some wells have low ratios, most wells had high cis/trans ratios between 26 and 684. This is taken as evidence of biodegradation at these locations.

Review of the redox geochemistry of groundwater at RFETS indicates that the groundwater in most wells is highly oxidizing with a mean DO content of 5.7 mg/L. However, there is evidence of locally reducing conditions suitable for biodegradation at a relatively small number of wells. For example, a few wells have elevated concentrations of ferrous iron that indicate an Fe(III) reducing environment suitable for biodegradation. Well 33502 has a mean ferrous content of 22 mg/L and has high concentrations of VC, confirming that biodegradation is taking place there.

ORP measurements in the RFETS groundwater range as low as -316 mV which is close to the range expected for sulfate reduction, another favorable indicator of biodegradation. Groundwater from some wells has detectable sulfide and anomalously low mole ratios of sulfate/sulfide implying that sulfate reduction is taking place.

BTEX is commonly found in groundwater contaminated by gasoline spills or leaking underground fuel tanks. Microorganisms use fuel hydrocarbons as a substrate or carbon source. Microbial respiration along with the biochemical oxygen demand (BOD) of fuel hydrocarbons and their degradation products, rapidly produce locally reducing conditions in groundwater. The combination of a food source for



bacteria and a reducing environment promotes CAH biodegradation. Therefore, the concentrations and location of BTEX in groundwater at RFETS is also an indicator of suitable biodegradation environments. Diesel fuel and hydraulic fluid from lathe coolant should also provide carbon sources for bacteria in groundwater.

BTEX concentrations in groundwater at RFETS were computed by summing the concentrations of analyzed isomers of xylene, benzene, toluene, and ethylbenzene at each well. Although BTEX is rapidly biodegraded, low concentrations of BTEX once existed in groundwater over much of the IA and East Trenches areas. This agrees with information from the Historical Release Report (DOE, 1992), that there were dozens of fuel spills, leaking tanks, and leaking drums at RFETS during its 50 year history. The highest BTEX concentrations were near the 903 Pad which was a drum storage site. Elevated BTEX concentrations were also observed at Ryan's Pit, East Trenches, and north of B-777.

A site-specific conceptual model was developed of natural attenuation processes at RFETS. This model assumes that typically uncontaminated groundwater at RFETS has a DO concentration averaging more than 5 mg/L in an aquifer low in DOC (e.g., BTEX). Such an environment does not support biodegradation by reductive dechlorination and is called a Type III groundwater environment (Wiedemeier et al., 1999).

Microbial respiration, and the potential presence of fuel hydrocarbons at CAH source areas causes rapid, but very local depletion of DO within the source contamination (PCE, TCE, CT). This may produce islands within the IA at IHSS 118.1, Mound, 903 Pad, or East Trenches where biodegradation locally takes place. These islands are surrounded by a sea of oxidizing groundwater which can aerobically oxidize VC, but does not support reductive dechlorination.

The site-specific conceptual model of biodegradation at RFETS is hypothesized to be a combination of a Type I environment at the island source area, surrounded by a Type III oxygenated environment. Figure 5-117 is a Site-specific conceptual model of natural attenuation at the RFETS.

The most important natural attenuation mechanisms for PCE, TCE, and CT in a Type III oxygenated environment are sorption, advection and dispersion. The lack of biodegradation in the Type III environment downgradient of the CAH source area allows the PCE and TCE plumes (Figure 5-117) to migrate relatively farther from the source than in the general conceptual model (Figure 3-5). Other differences between the general and Site-specific models are listed below:

- Background and downgradient DO levels are higher in the Site-specific model (Figure 5-117);
- Although PCE and TCE have longer plumes, VC has a shorter, narrower plume because it can be aerobically oxidized by downgradient DO;



- Methane, acetate, and sulfide have smaller areas of chemical stability within the plume because they can be oxidized downgradient or consumed by aerobic bacteria;
- Redox zonation is typically smaller around the Type I biodegradation environment; and
- If Mn(IV) and Fe(III) reduction produced elevated concentrations of Mn(II) and Fe(II) at and just below the source area; these metals may re-oxidize downgradient.

This report has met its objective of providing biodegradation rate constants to support transport modeling of CAHs in the Site groundwater. It has provided an assessment of the occurrence and natural attenuation of CAHs in groundwater at the RFETS. This assessment provides valuable input for DOE strategic planning of groundwater remediation and Site closure. The assessment should also be useful to WMCP and ER personnel in rescoping groundwater monitoring needs, and evaluating potential remedial actions for groundwater.



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#### APPENDIX A

# NATURAL LOG CONCENTRATION VERSUS ELAPSED TIME PLOTS FOR SELECTED FLOWPATHS

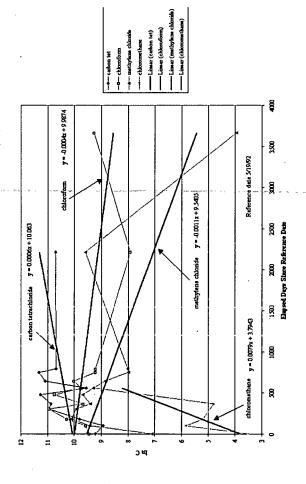
252

88 y = -0.0002x + 3.7304 009 C vs T Rot PSA2A Well 01291 Carbon Tetrachloride Series Detects y = -0.0002x + 7.9814 Reference date 9/10/87 8 y = 2E-05x + 2.2745 1400 y = .3E.05x + 3.1534 8 8 Dagged Days Since Reference Date <u>8</u> 8 8 8 800 Reference date 3/21/92 8 8 3, 23 -13. ŝ Ş эщ рς 450 C vs T Hot PSA2A Well 00491 Carbon Tetrachloride Detects C vs T Rot PSA2A Well 0987 Chloroform Series Detects 8 3300 y=-0.0006x+2.4504 Carbon tetrachlonde was not detected in this well. 3000 8 Elapsed Days Since Reference Date Elapsed Days Since Reference Date 2300 methylene chloride 8 y = -0.0003x + 5.4812 CT regression 900 chloroform regression y = -0.0002n: + 4.5208 9<u>8</u> 2000 ĕ Reference date 10/12/87 Reference data 12/20/91 8 ğ 5. 5 ş ÷. эщ

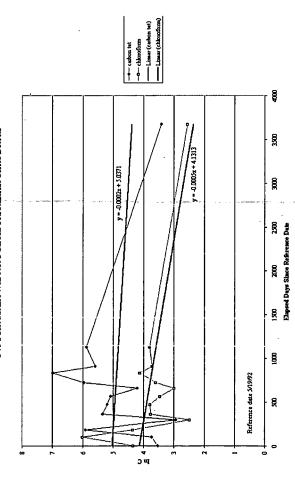
C vs I Hot PSA2A Well 1587 Carbon Tetrachloride Series Detects

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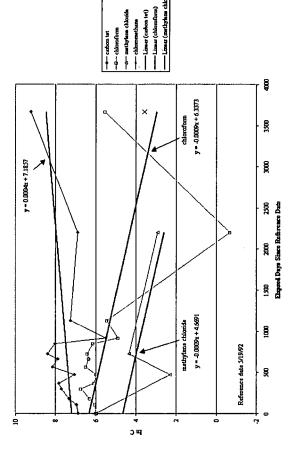
C vs T Flot PSA2A Well 06691 Carbon Tetrachloride Series Detects



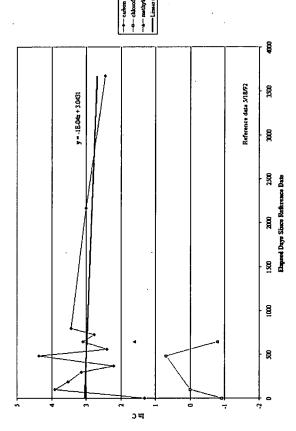
C vy T Hot PSA2A Well 06591 Carbon Tetrachloride Series Detects



C vs T Flot PSA2A Well 13191 Carbon Tetrachloride Series Detects



C vs T Hot PSA2A Well 06991 Carbon Tetrachloride Series Detects



300 1300 1000 Perference data \$/5/99 Reference date 2/25/98 (1st nodus) meni l (emoltonolde) wanil-20.00+±2000.0 = ₹ hat moduso ---A = 0.0003x + 0.9524 C vs T Flot PSALA Well 90299 Carbon Tetrachloride Series Detects C vs T Mot PSA2A Well 23196 Methylene Chloride Detects Elegated Days Since Reference Date Dapeed Days Since Reference Date 4200 0000 3200 0001 900 320 001 Reference data 12/20/91 Reference Date 7/31/02 (stratic startin) wani I ----Linea (sulfate) - Linear (chloride) — mengenese (filtered) 40 -e-(bereiff) nori --10-← ~721.8+±5000.0- -₹ ets'lius ----a- chloride ---- bicarbonate P- 0.0002x+11.54

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C vs T Flot PSAZA Well 00491 MINA Indicator Analytes

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C vs T Flot FSAAA Well 50099 Carbon Tetrachloride Series Detects

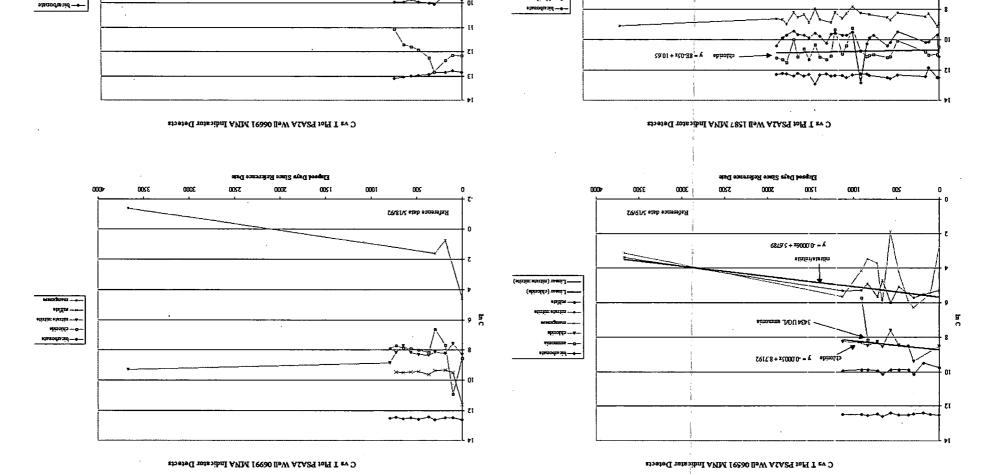
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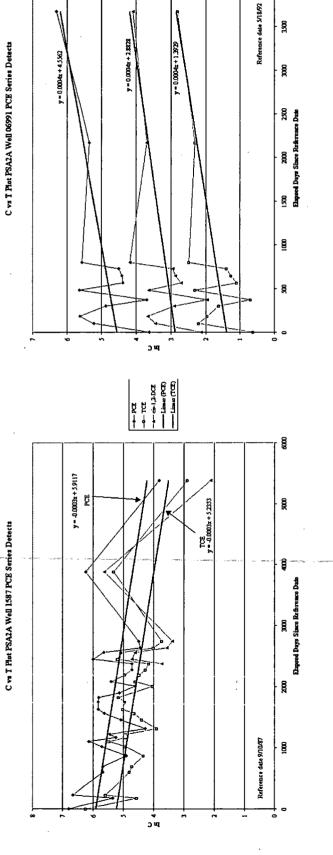
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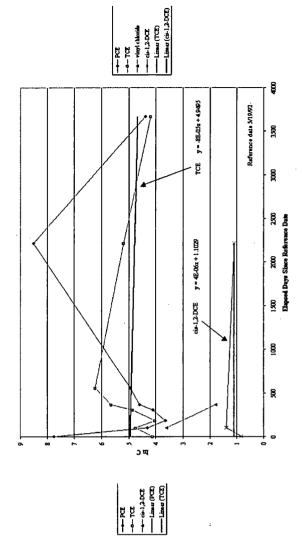
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C vs T Flot PSA2A Well 1587 PCE Series Detects



C vs T Hat PSA2A Well 06691 PCE Series Detects

C vs T Ret PSA2A Well 01291 PCE Series



y = 0.0002x + 0.0342

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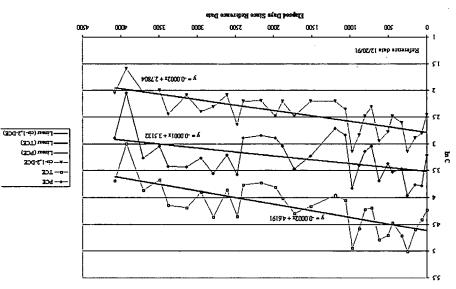
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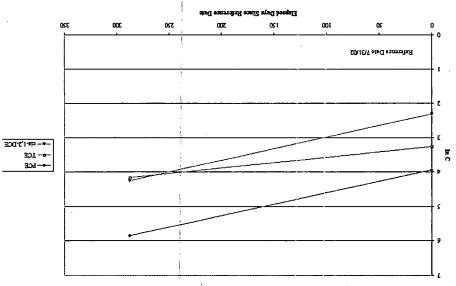
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Dapoed Days Since Reference Date

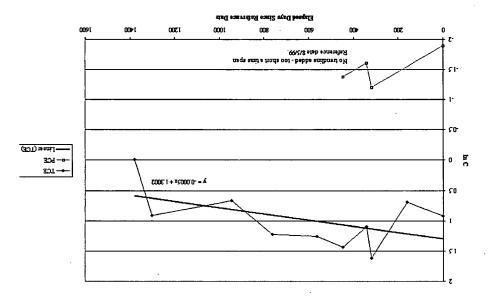
C vs T Flot PSA2A Well 00491 PCE Series Detects



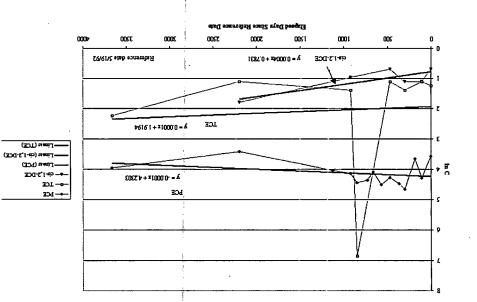
C vs T Flot PSALA Well 50099 PCE Series Detects



C vs T Plot PSALA Well 90299 PCE Series Detects

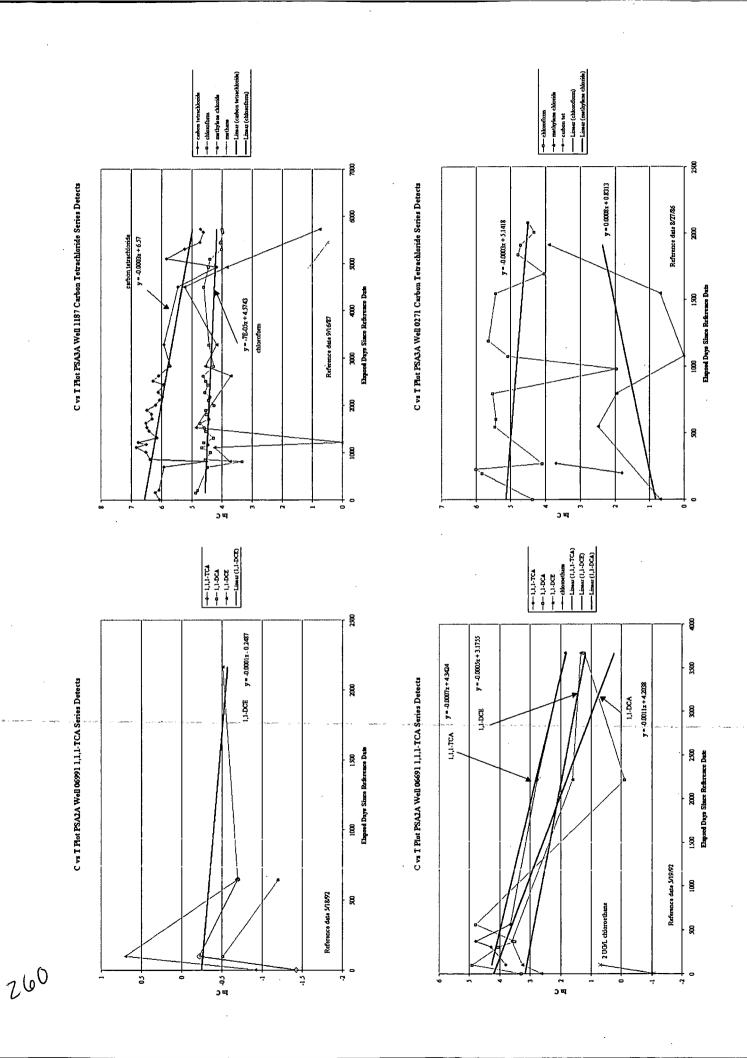


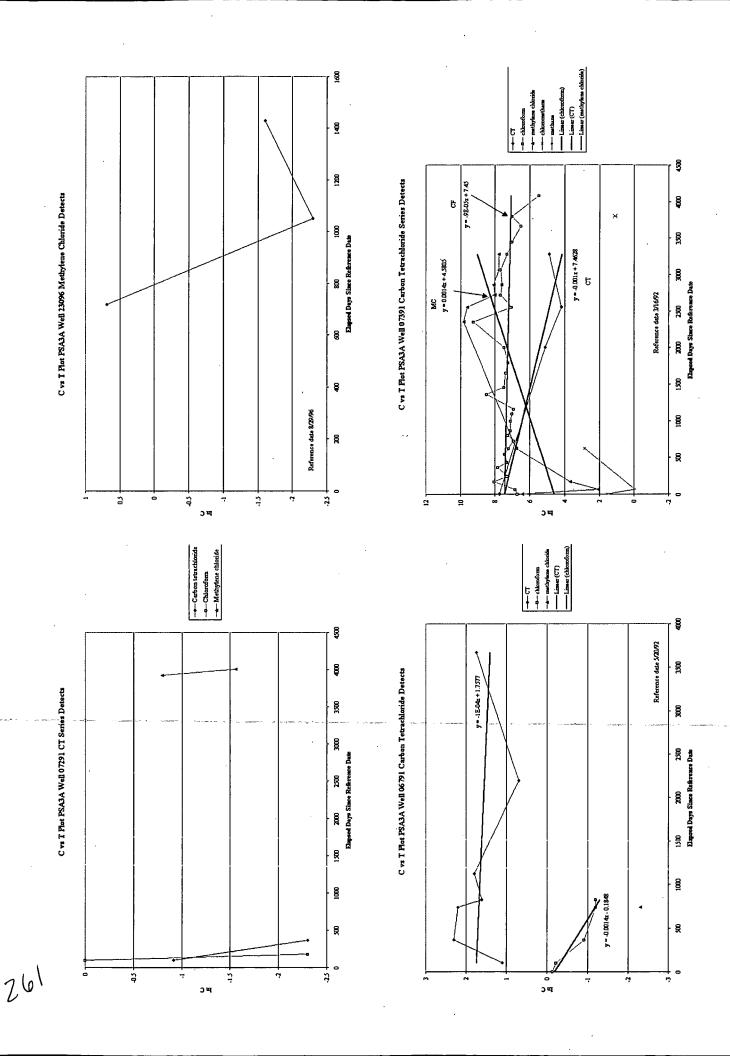
C vs I Not PSALA Well 13191 PCE Series Detects

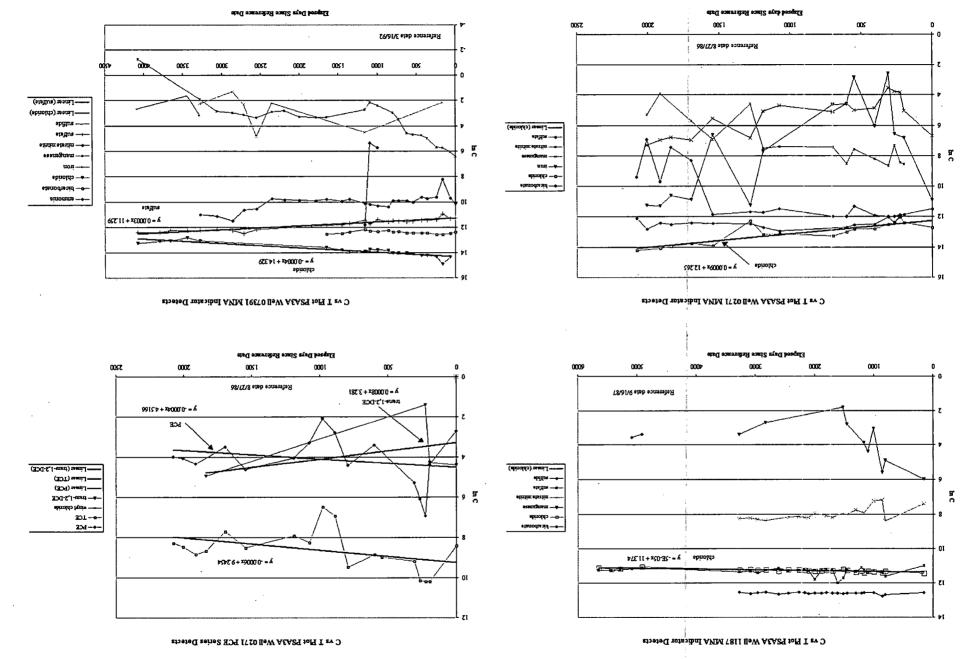


---1,1,1-TCA -8-1,1-DCA ---1,1-DCE ----Linew(1,1-DCA) y = -0.0001x + 1.2366 Reference data 5/19/92 8 8 C vs T Hot PSA2A Well 1587 1,1,1-TCA Series Detects 暴 y = -4E-05x+1.722 3300 Ş 1,1-DCE 99 2000 2500 : Eupeed Days Since Reference Date Daysod Days Since Reference Date 8 y=0.0035x - 0.3461 951 1,1-DCA 욢 **8**9 8 Reference date 9/10/87 8 8 эщ **₽¢** 5 5 ÷ Ş ---1,1,1.7Ca ---1,1.0Ca ---1,1.0Ca ---1,1.0Cz ---1,1.0Ca ---1,1.0Ca) 8 y = 6E.05x + 2.8041 Reference date 12/20/91 Reference date 5/19/92 1.1 DCE y = -0.0001x - 0.6121 88 88 C vs T Hot PSA2A Well 00491 TCA Chain Detects C vs I Hot PSA2A Well 13191 TCA Detects y = -1E-05x - 1.1691 y = -0.0005x + 2.6482 2000 2500 ::
Expeed Days Since Reference Date 1,1,1-TCA y = -0.0004x + 1.5182 11.DCA 8 8 ğ g Pro Co

C vs T Flot PSA2A Well 06591 1,1,1-TCA Series Detects



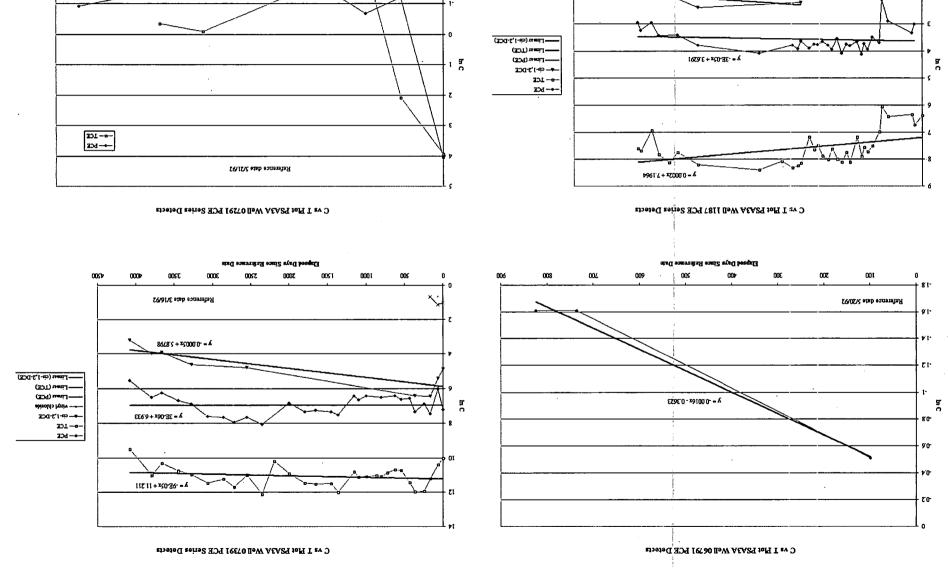




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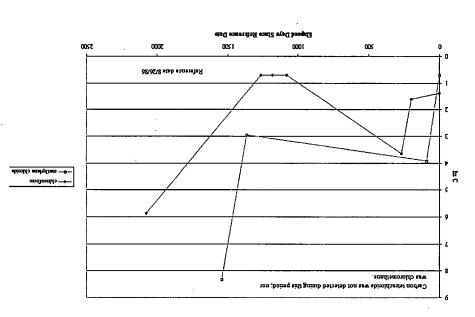
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Reference date 9/16/87

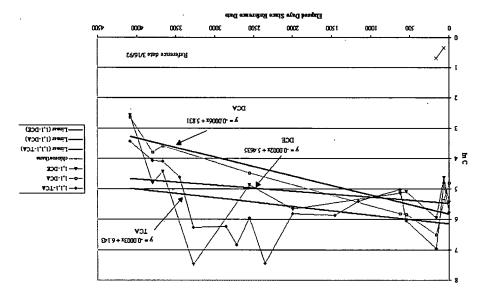


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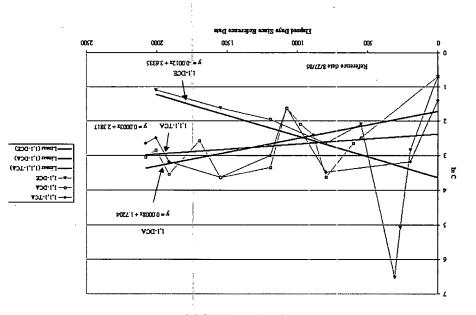
C vs T Hot PSASA Well 0174 Chloroform Series Detects



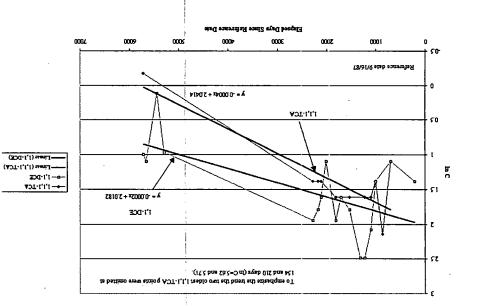
C vs T Plot PSA3A Well 07391 I, I, I-TCA Series Detects

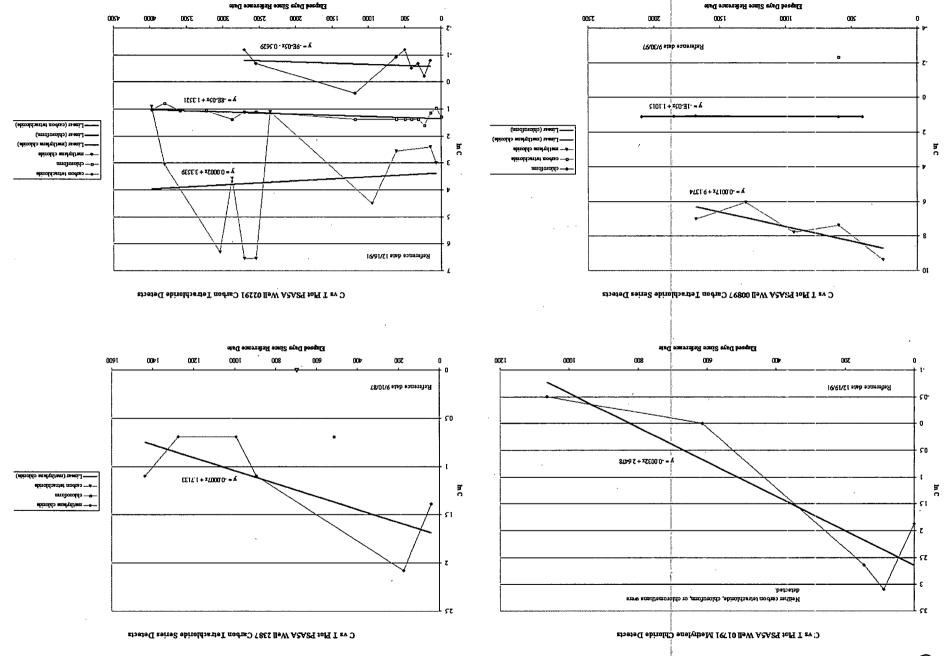


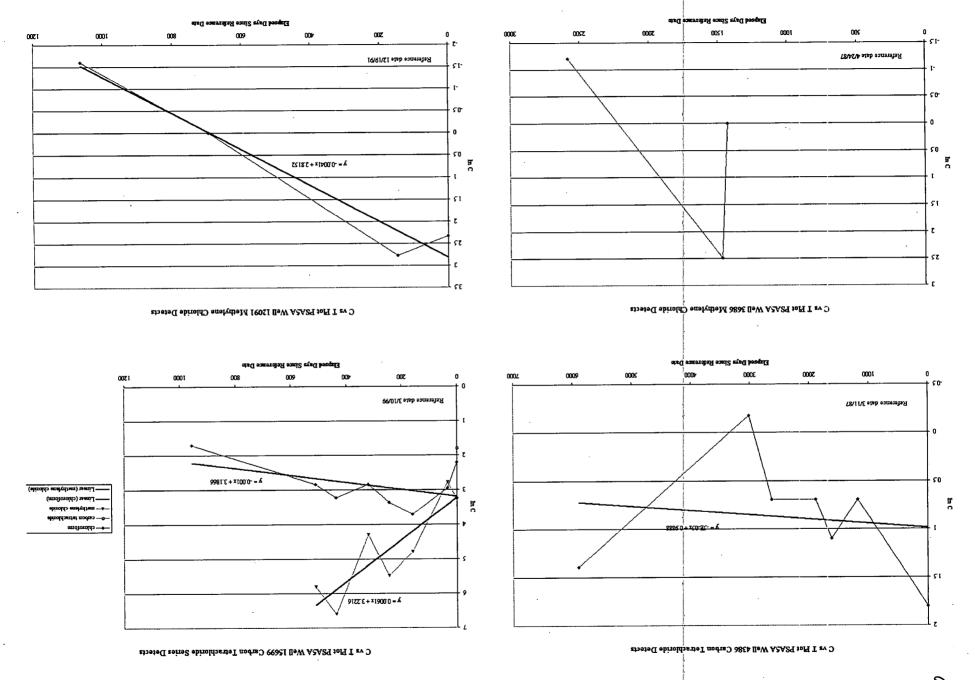
C vs T Flot PSA3A Well 0271



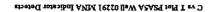
C vs T Flot PSA3A Well 1187 I,1,1-TCA Series Detects

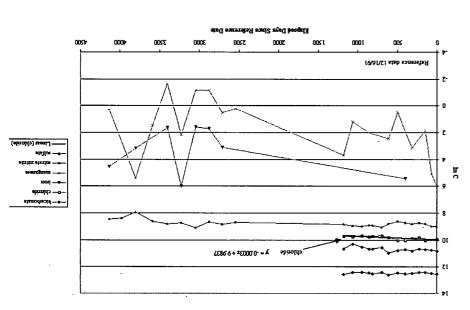




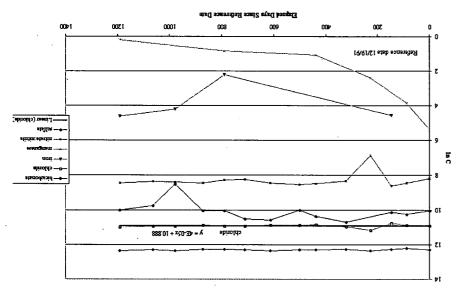


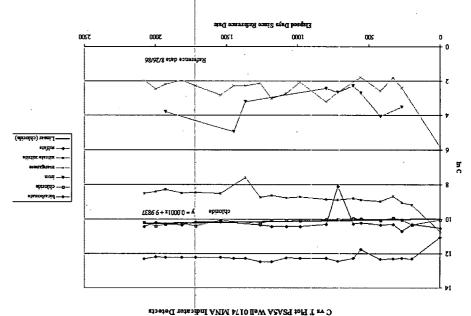




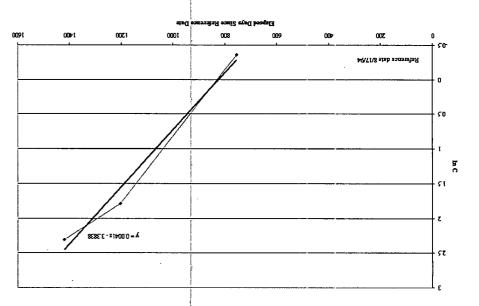


C vs T Plot PSASA Well 01791 MINA Indicator Detects

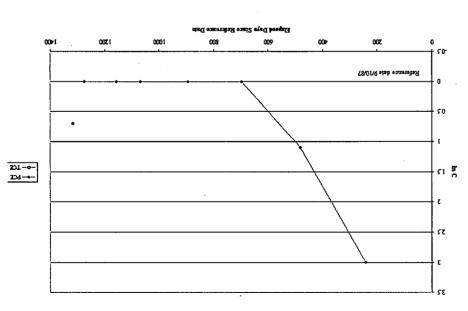


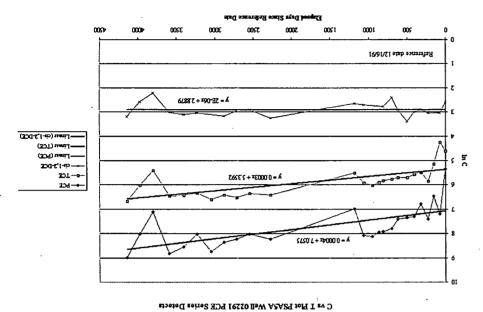


C vs T Flot PSASA Well 75992 Methylene Chloride

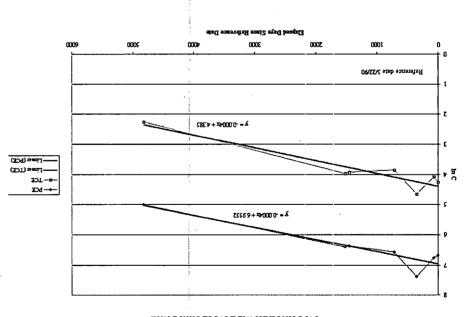


C vs T Mots PSASA Well 2387 PCE Series Detects

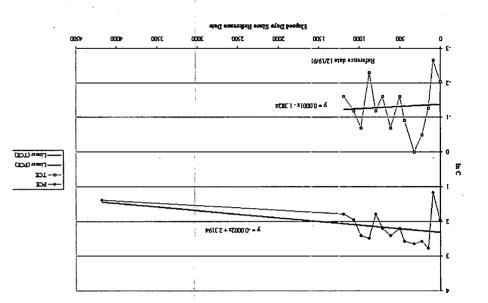


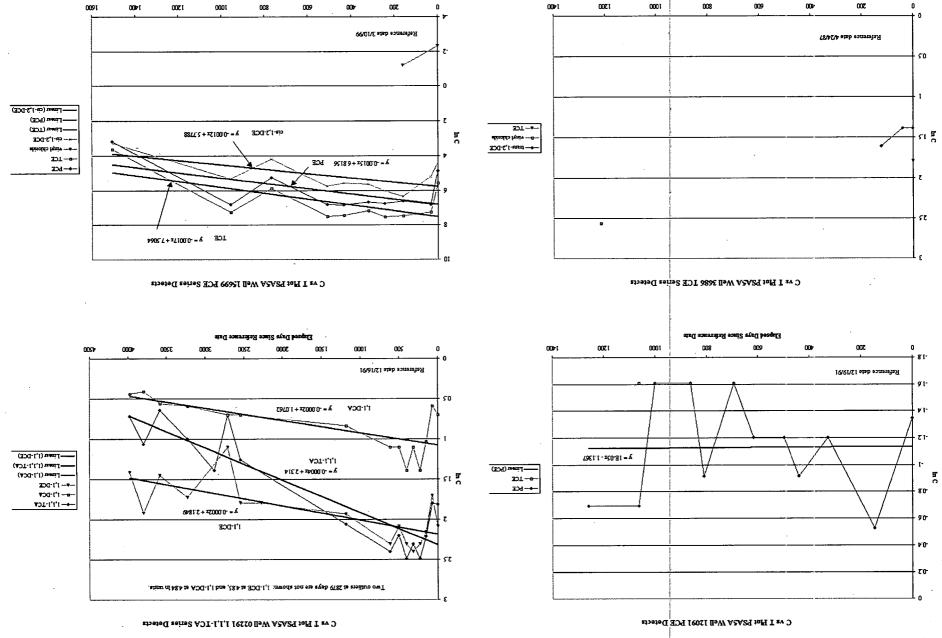


C vs T Hot PSASA Well 1987 PCE Series Detects



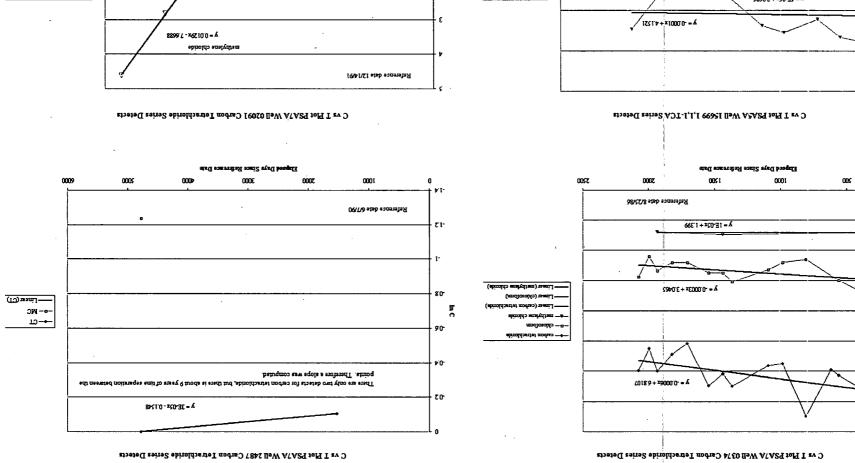
C vs T Hot PSASA Well 01791 PCE Series Detects





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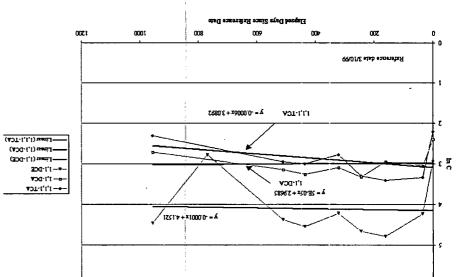
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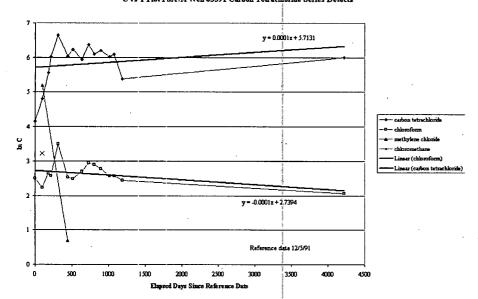
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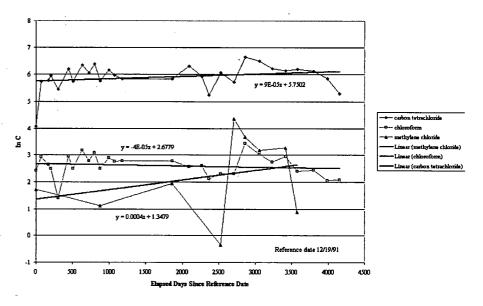
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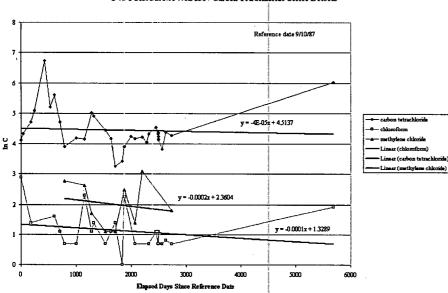
### C vs T Plot PSA7A Well 03391 Carbon Tetrachloride Series Detects



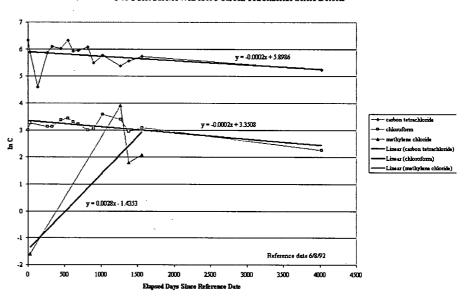
### C vs T Plot PSA7A Well 11891 Carbon Tetrachloride Series Detects



### C vs T Plot PSA7A Well 2587 Carbon Tetrachloride Series Detects



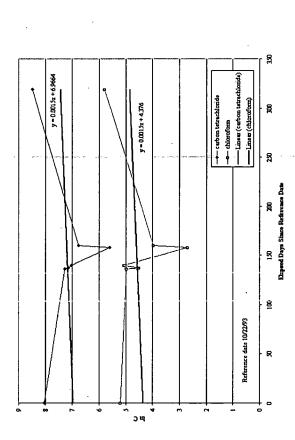
### C vs T Plot PSA7A Well 03691 Carbon Tetrachloride Series Detects



C vs I Hot PSA7A Well 24193 Carbon Tetrachloride Series Detects

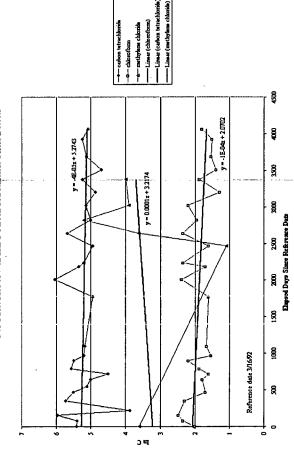
chloride y = -8E-06x + 10 939

C vs T Hot PSA7A Well 02091 MINA Indicator Detects



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C vs T Hot PSA7A Well 12191 Carbon Tetrachlonide Series Detects



C vs T Flot PSA7A Well 24393 Carbon Tetrachloride Series Detects

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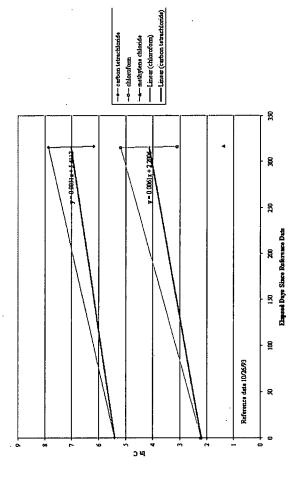
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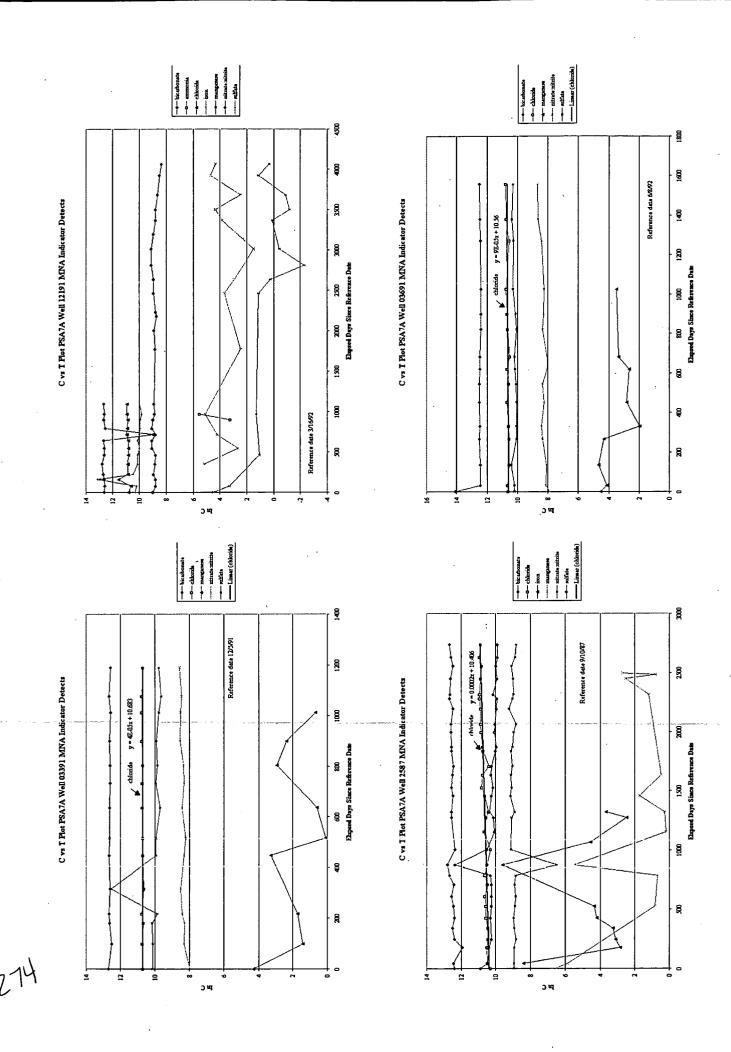
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Reference date 12/14/91

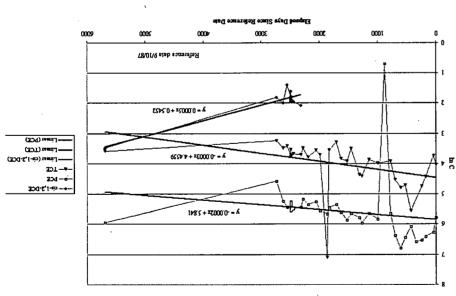
Elapsed Days Since Reference Date



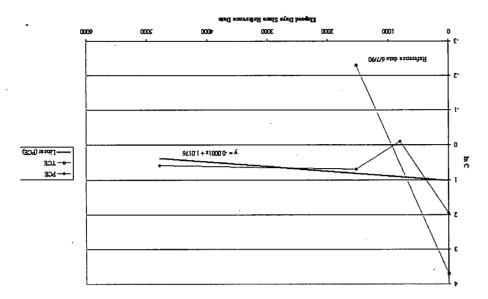




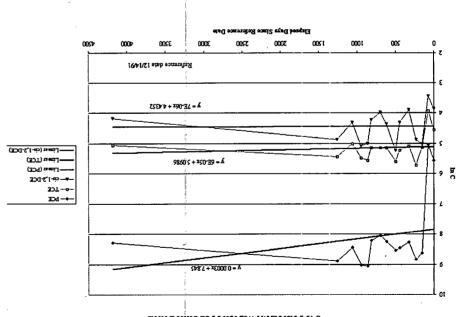




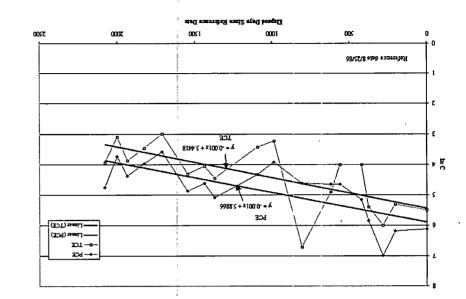
C vs I Plot PSA7A Well 2487 PCE Series Detects

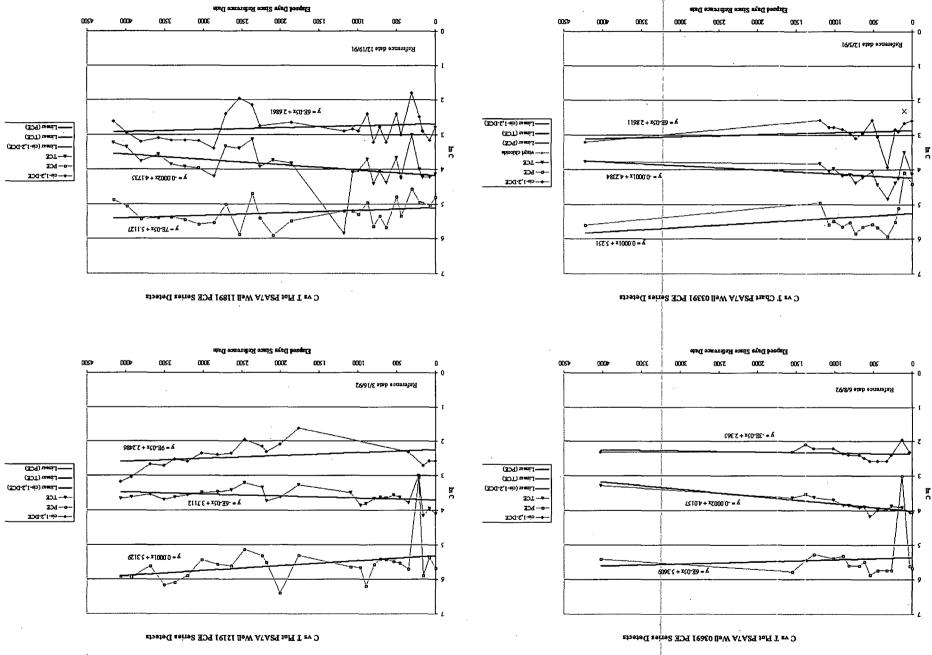


C vs T Hot PSA7A Well 02091 PCE Series Detects

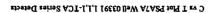


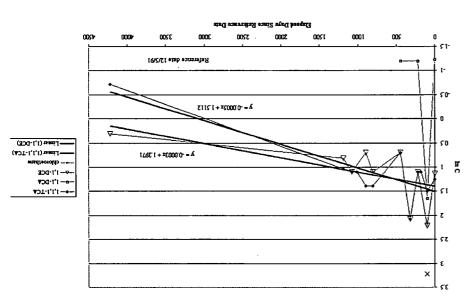
C vs T Flot PSA7A Well 0374 PCE Series Detects



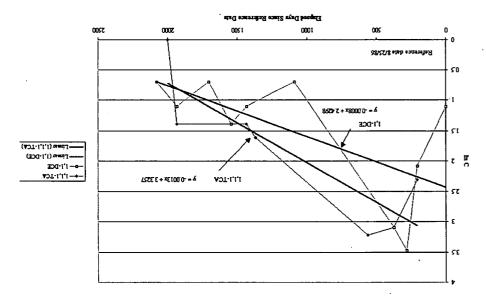




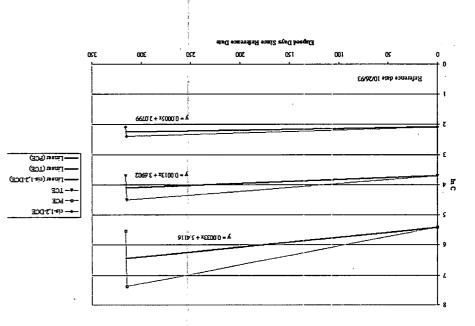




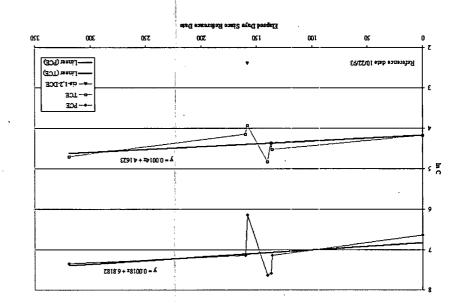
### C vs T Plot PSA7A Well 0374 I, I, I-TCA Series Detects

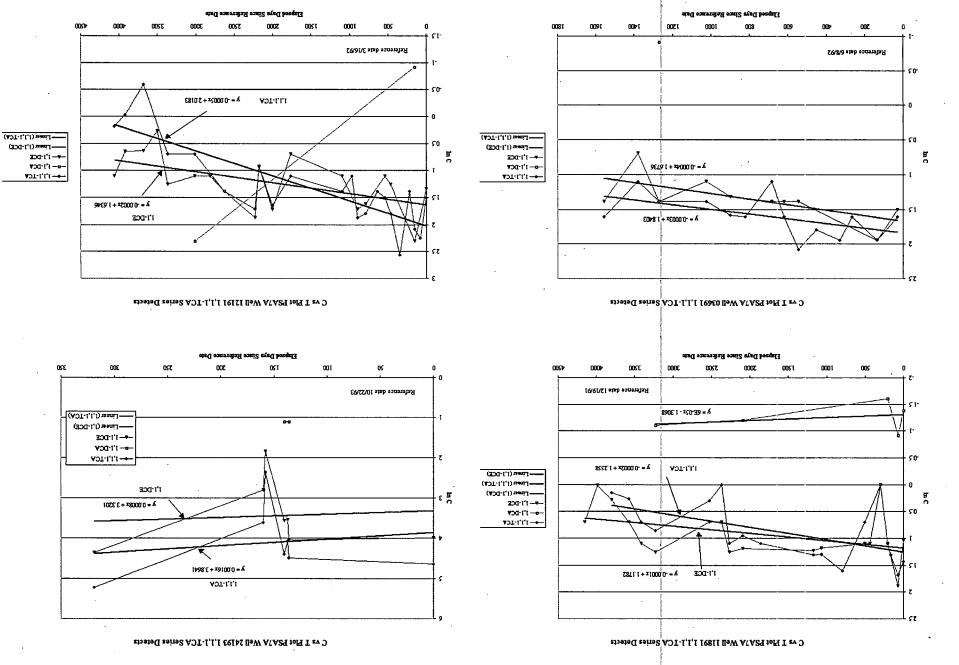


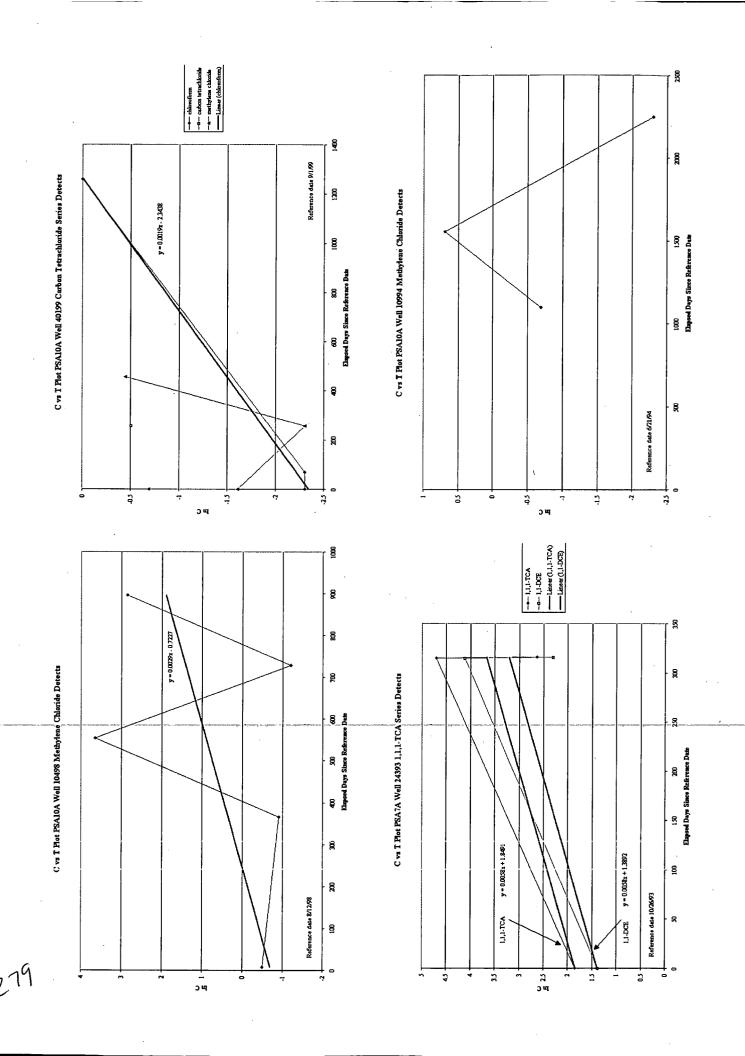
C vs T Plot PSA7A Well 24393 PCE Seifes Detects

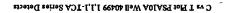


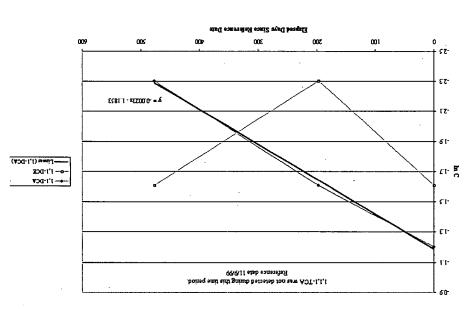
C vs T Hot PSA7A Well 24193 PCE Series Detects



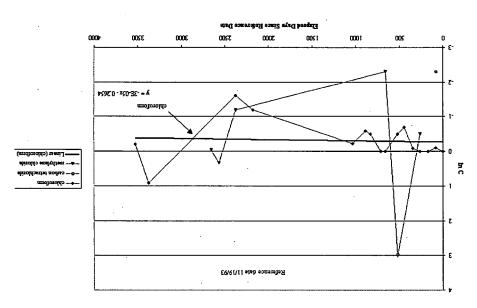


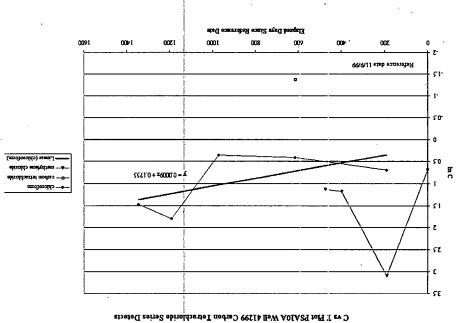




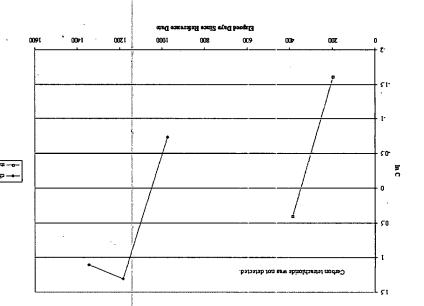


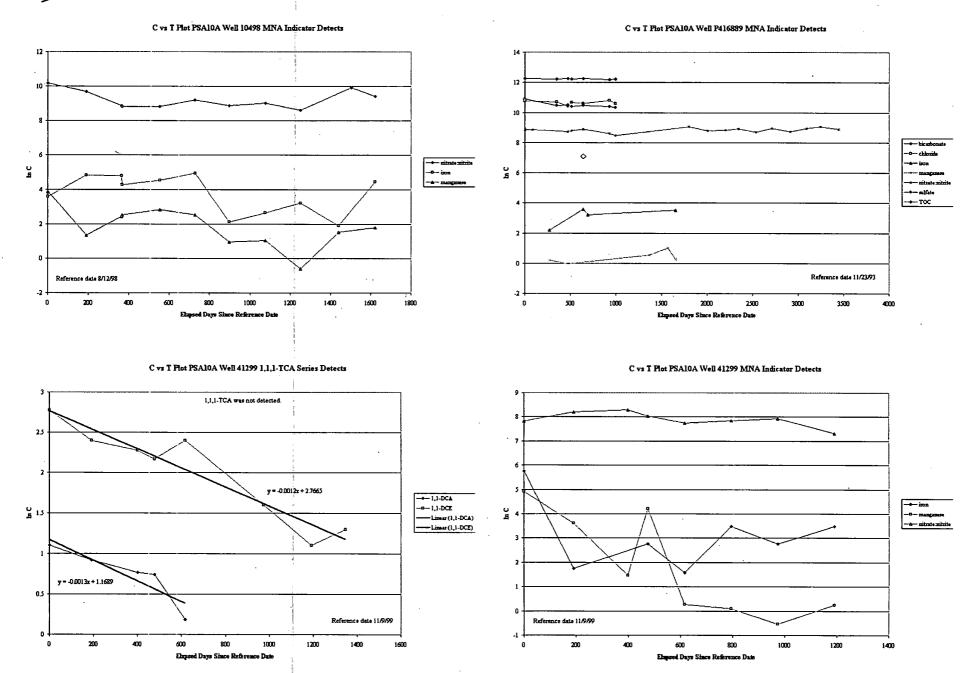
C vs T Mot PSA10A Well P419689 Carbon Tetrachloride Series Detects





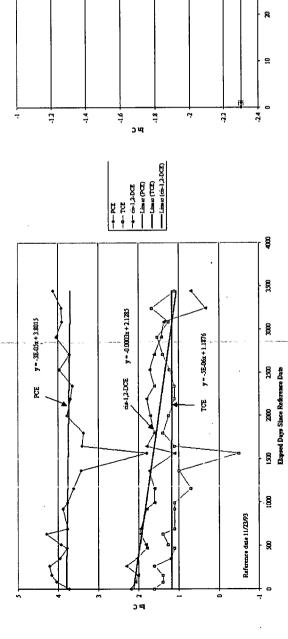
C vs T Flot PSAloA Well 40499 Carbon Tetrachloride Series Detects



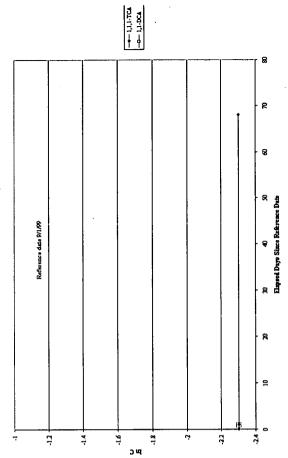


-e-PC -e-TC -e-c-1,2-DC Reference date 9/1/99 8 y = 0.0023x - 0.6508 8 C vs T Flat PSA10A Well 40499 PCE Series Detects C vs T Hot PSA10A Well 40199 PCE Series Detects 82 1200 y = -0.0012x + 2.4631 600 800 1000 Dapod Days Since Reference Date 600 800 1000 Expeed Days Since Reference Date Reference date 11/9/99 y = -0.0012x + 0.9998 y = -0.0013x + 2.0976 8 ä 8 ٠ ک рς рς Reference date \$12.98 3300 C vs T Hots PSA10A Well P419689 MINA Indicator Detects y = 0.0005x + 3.3305 8 C vs I Hot PSA10A Well 10498 PCE Series Detects 230 Daysed Days Since Reference Date 800 1000 1200 Daysed Days Since Reference Date y = 0.0006x - 1.9009 Control of the Control 8 y = 0.0042x - 3.0591 贸 Reference date 11/19/93 8 쥝 рщ ь рис 2 2

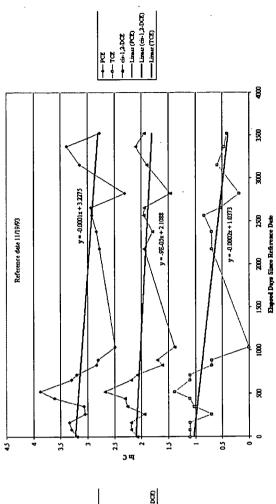
### C vs T Plut PSA10A Well P416889 PCE Series Detects



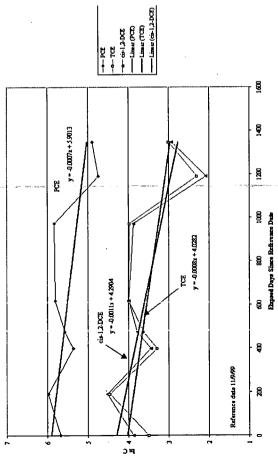
## C vs T Hot PSA10A Well 40199 1,1,1-TCA Series Detects

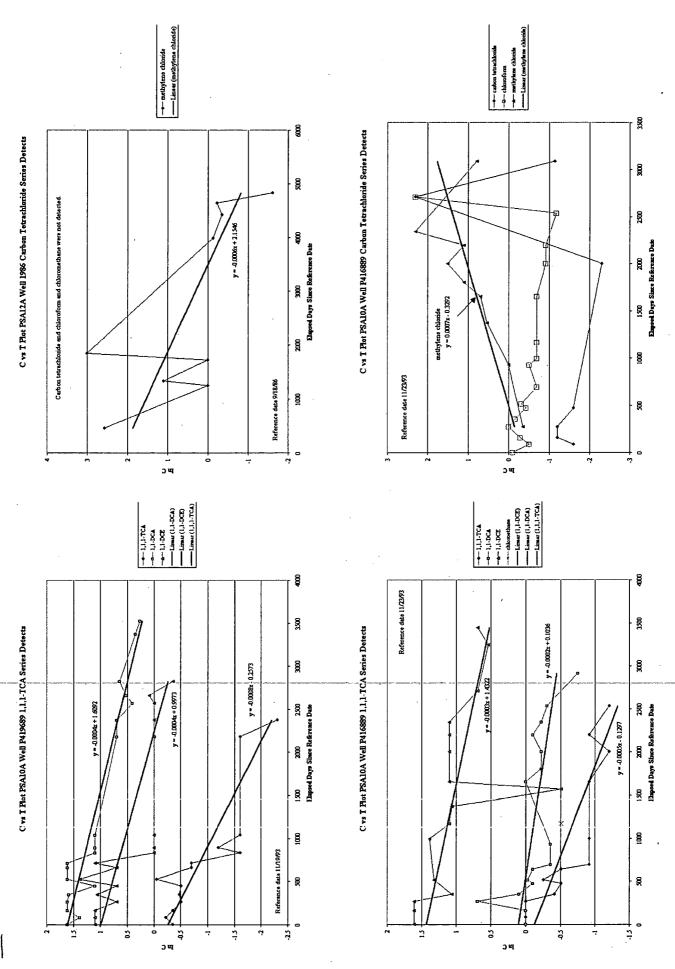


## C vs T Flot PSA10A Well P419689 PCE Series Detects

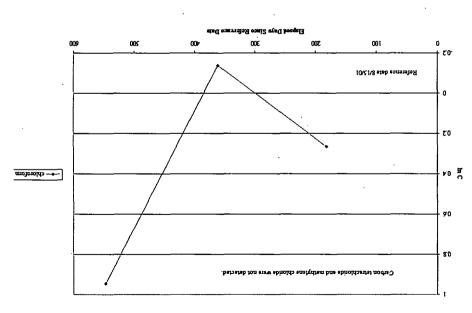




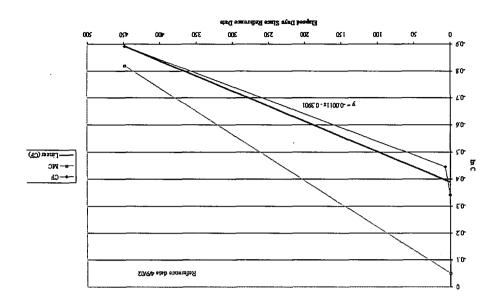




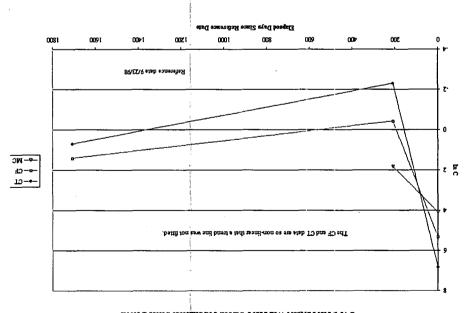




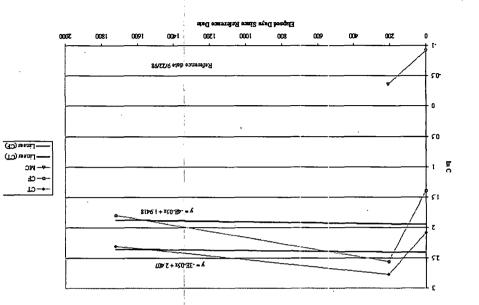
### C vs T Hot PSAL2A Well 84702 Carbon Tetrachloride Series Detects



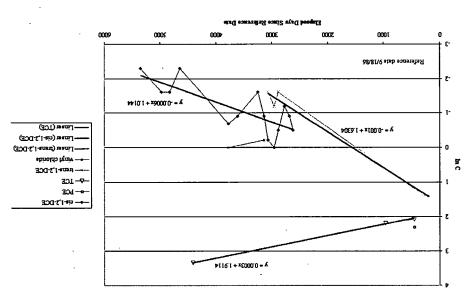
### C vs T Flot PSALLA Well 21598 Carbon Tetrachloride Series Detects



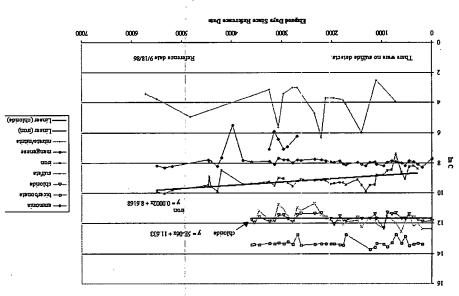
### C vs T Flot PSALLA Well 21298 Carbon Tetrachloride Series Detects



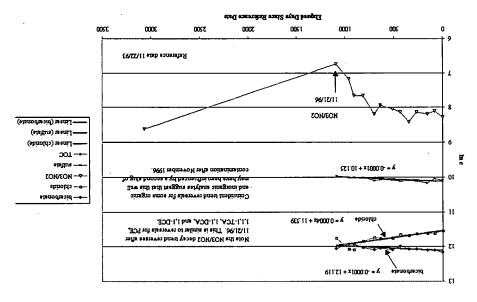
C vs T Plat PSALLA Well 1986 PCE Series Detects



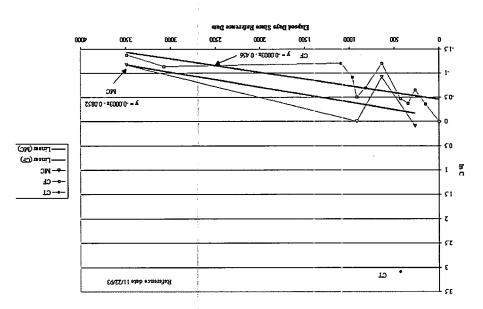
C vs T Plot PSALLA Well 1986 Biodegradation Indicators

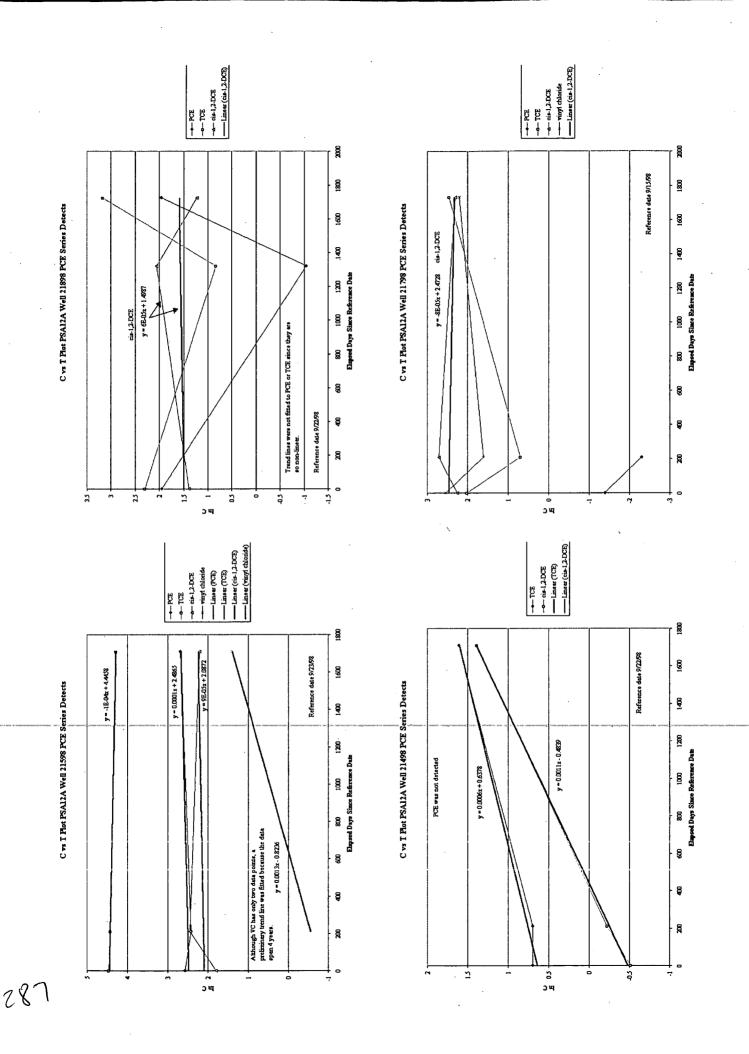


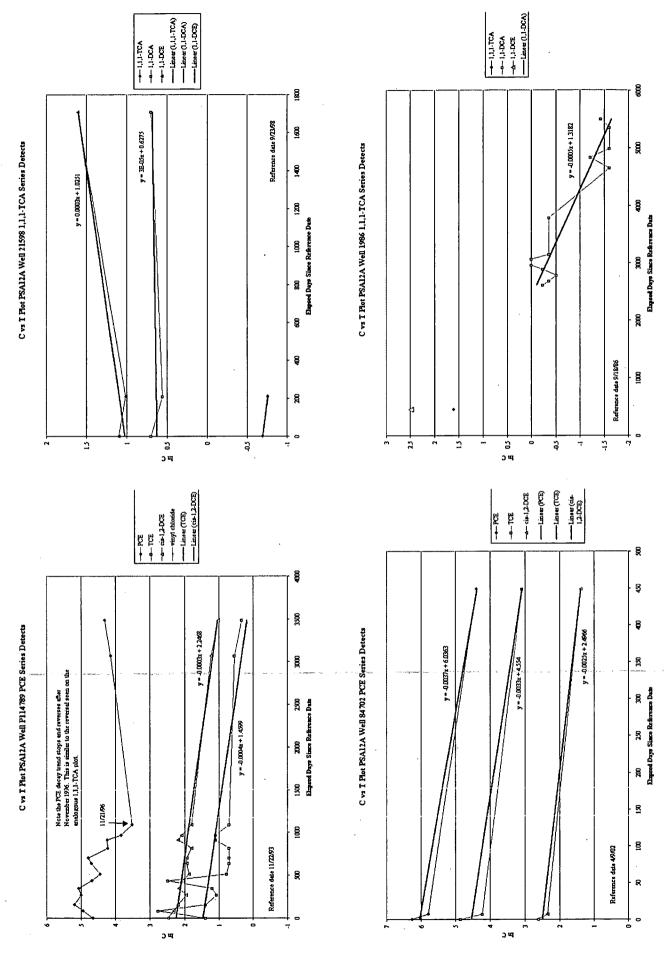
C vs T Flot PSALLA Well P114789 Indicator Personeter Detects



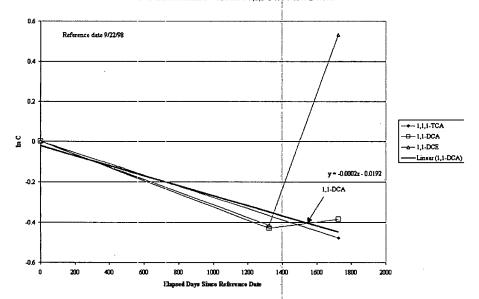
C vs T Plot PSAl2A Well P114 789 Carbon Tetrachloride Series Detects



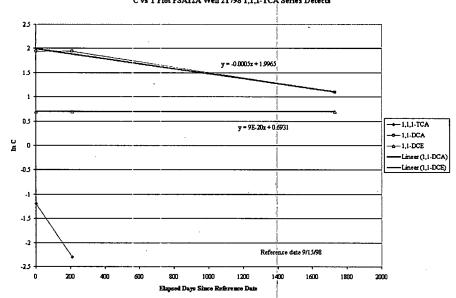




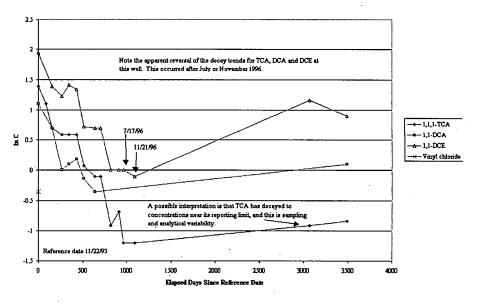
### C vs T Plot PSAL2A Well 21898 1,1,1-TCA Series Detects



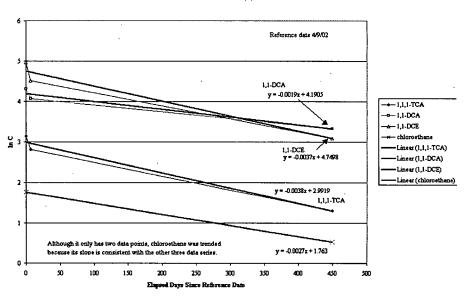
### C vs T Plot PSA12A Well 21798 1,1,1-TCA Series Detects



### C vs T Plot PSA12A Well P114789 1,1,1-TCA Series Detects



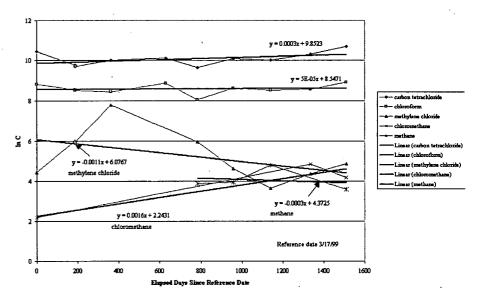
### C vs T Plot PSA12A Well 84702 1,1,1-TCA Series Detects



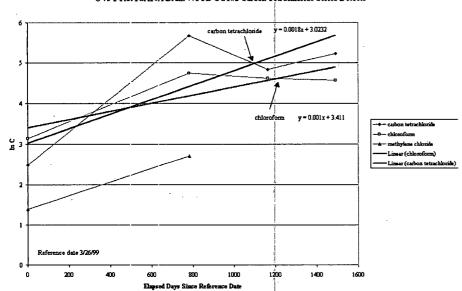


# y = 0.0005x + 9.6625 y = 0.0004x + 7.944 y = 0.0002x + 6.4405 y = 0.0002x + 6.4405 y = 0.0002x + 6.4405 Linux (caston terchlorids) Linux (caston terchlorids)

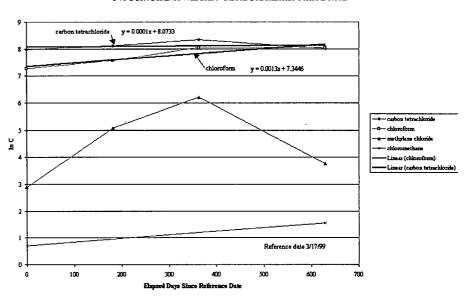
### C vs T Plot PSA14A Well 18499 Carbon Tetrachloride Series Detects



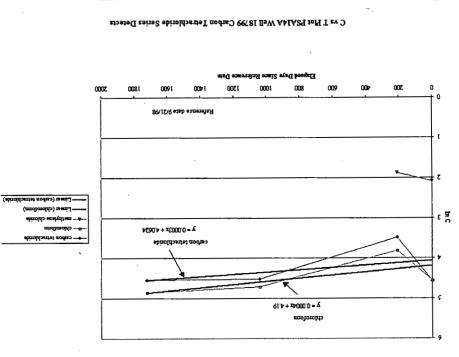
### C vs T Plot PSA14A Drain 771 FD OUT#2 Carbon Tetrachloride Series Detects

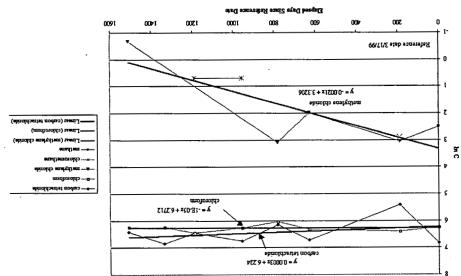


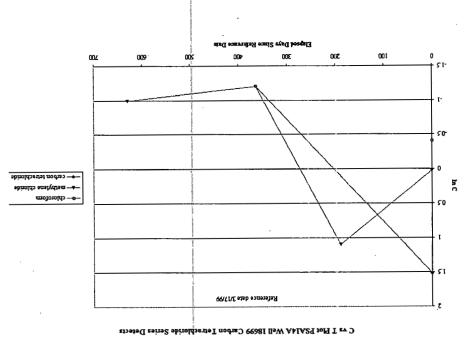
### C vs T Plot PSA14A Well 18299 Carbon Tetrachloride Series Detects



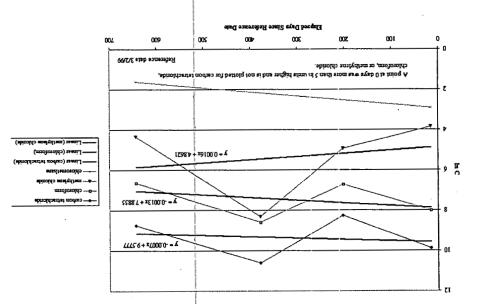
C vs T Mot PSAL4A Well 20898 Carbon Tetrachloride Series Detects





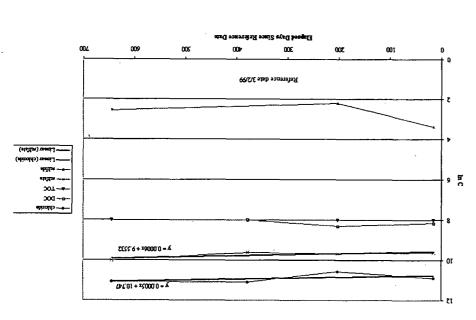


C vs T Flot PSAL4A Well 18599 Carbon Tetrachloride Series Detects

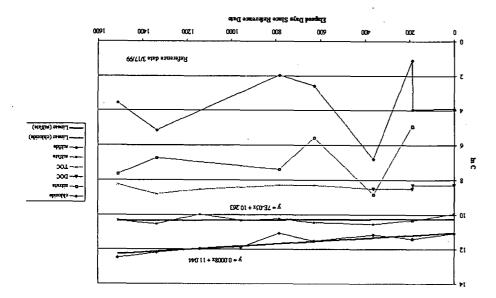


chloroform y = -0.0002x + 0.0318 8 C vs T Hot PSA14A Well 226% Carbon Tetrachloride Series Detects C vs T Plot PSA14A Well 21098 Carbon Tetrachloride Series Detects 1200 8 ă ĕ 800 1000 1200 Append Days Since Roference Date Daysed Days Since Reference Date Reference date 9/22/98 · y = -0.0006x + 6.0863 8 8 Reference date 2/4/97 8 эщ C vs T Plot PSA14A Well 20998 Carbon Tetrachloride Series Detects C vs T Hot PSA14A Well 21002 Carbon Tetrachlonde Senes Detects ន្ត 1000 1000 y=0.0016x+3.8129 y = -0.0002x + 4.3967 y = -0.0023x + 2.6672 Dapsed Days Since Reference Date Dapsed Days Since Reference Date Reference date 11/11/02 젎 y = 0.0024x + 0.0704 y = 0.0008x + 5.2695 y = -0.003-4x + 8.0006 Reference date 9/22/98 R 292

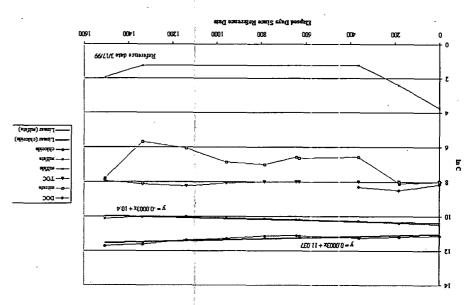
C vs T Hot PSAL4A Well 18599 MINA Indicator Detects



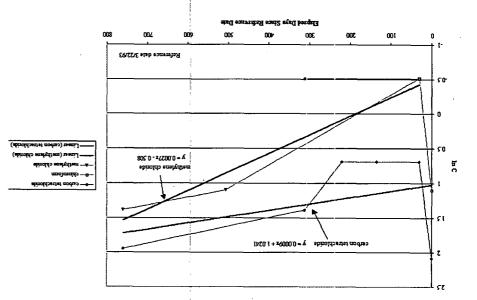
C vs T Mot PSAl4A Well 18499 MIVA Indicator Detects

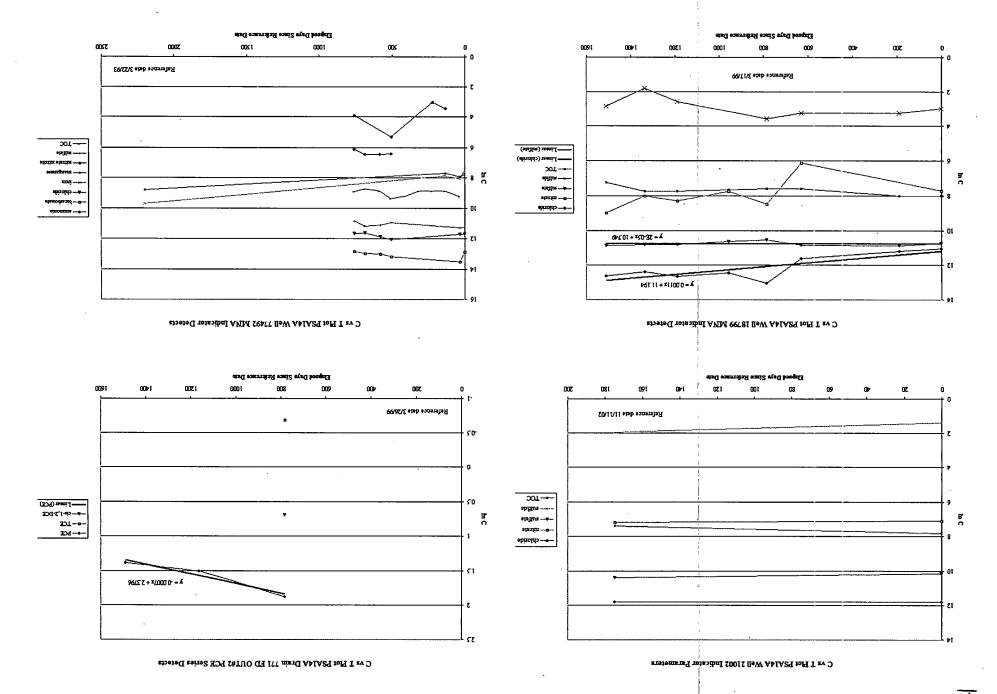


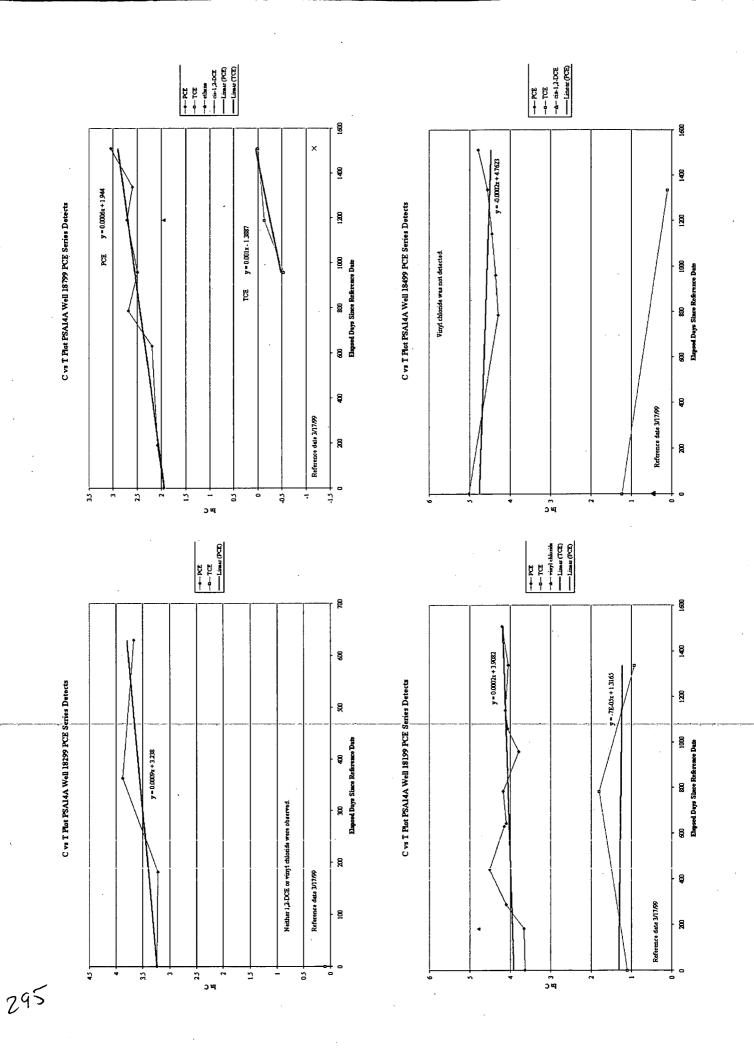
C vs T Plot PSAL4A Well 18199 MINA Indicator Detects

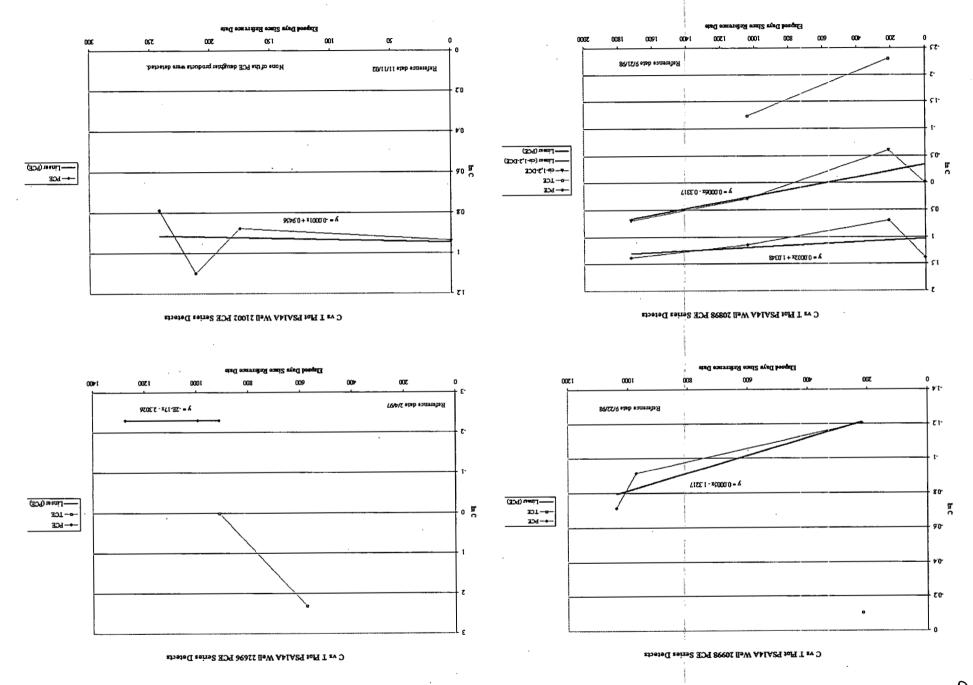


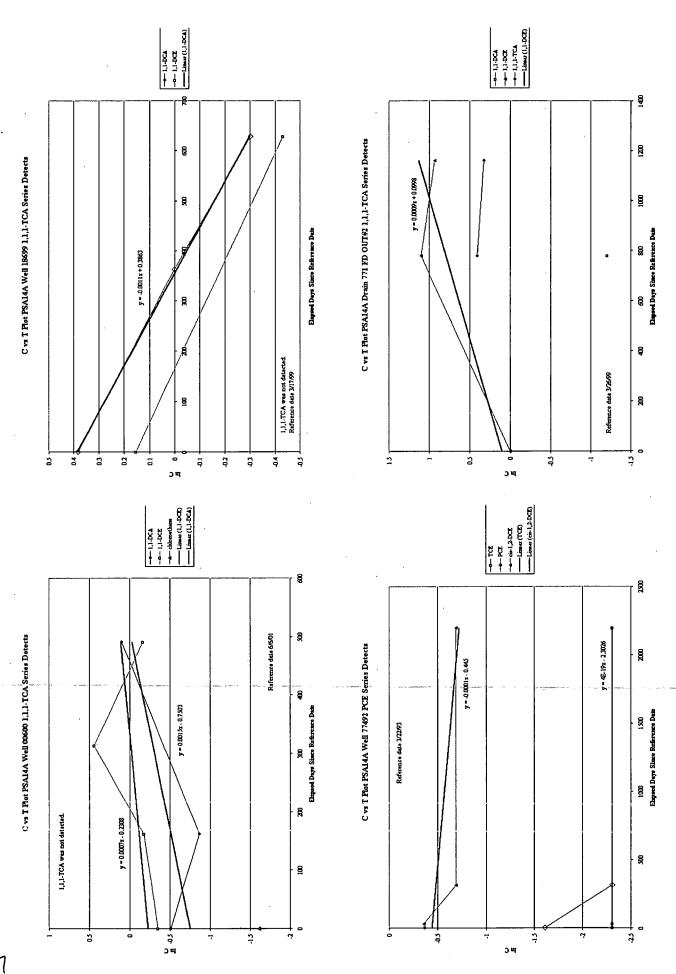
C vs T Flot PSAl4A Well 77492 Carbon Tetrachloride Series Detects

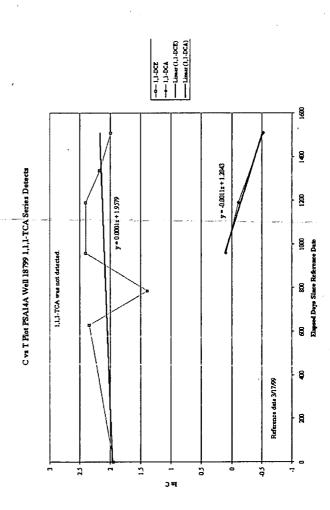












## APPENDIX B

# POINT ATTENUATION RATE CONSTANT CALCULATIONS AND SUPPORTING DATA

DC 4	Flow-	W 11 2	Charita	Tier II	Reference	lnC vs T	lnC	Intercept	k point	k point	half-life	half-life	decay time	decay time	Predicted Date # of	Predicted Date of Meeting
PSA	path	Well #	Chemical	Goal ug/L	Date of Plot	Slope (per day)	Intercept (In units)	(ug/L)	(per day)	(рег ут)	(days)	(years)	(days)	to meet goal (yr)	Meeting Goal	Goal if it continues to decay
. 2	Α	00491	1,1-DCA	3650	12/20/1991	-0.00001	-1.16910	0.3	0.00001	0.00365	69310.0	189.76	-937158.2	-2565.80	-903566	Goal was never exceeded
2	Α	00491	1,1-DCE	7	12/20/1991	-0.00010	-0.61210	0.5	0.00010	0.03653	6931.0	18.98	-25580.1	-70.03	8012	Goal was never exceeded
2	Α	00491	CF	100	12/20/1991	-0.00020	4.52080	91.9	0.00020	0.07305	3465.5	9.49	-421.9	-1.15	33170	October 24, 1990
2	Α	00491	cis-1,2-DCE	70	12/20/1991	-0.00020	2.78040	16.1	0.00020	0.07305	3465.5	9.49	-7340.5	-20.10	26252	November 14, 1971
2	Α	00491	CT	. 5	12/20/1991	-0.00030	5.48120	240.1	0.00030	0.10958	2310.3	6.33	12905.9	35.33	46498	April 20, 2027
2	Α	00491	PCE	5	12/20/1991	-0.00010	3.51320	33.6	0.00010	0.03653	6931.0	18.98	19037.6	52.12	52630	February 2, 2044
2	Α	00491	TCE	5	12/20/1991	-0.00020	4.61910	101.4	0.00020	0.07305	3465.5	9.49	15048.3	41.20	48640	March 2, 2033
2	Α	01291	CF	100	5/21/1992	-0.00003	3.15340	23.4	0.00003	0.01096	23103.3	63.25	-48392.3	-132.49	-14647	Goal was never exceeded
2	Α	06591	CF	100	5/19/1992	-0.00050	4.13130	62.3	0.00050	0.18263	1386.2	3.80	-947.7	-2.59	32795	October 14, 1989
2	Α	06591	CT	5	5/19/1992	-0.00020	5.03710	154.0	0.00020	0.07305	3465.5	9.49	17138.3	46.92	50881	April 21, 2039
2	Α	06691	1,1,1-TCA	200	5/19/1992	-0.00070	4.34240	76.9	0.00070	0.25568	990.1	2.71	-1365.6	-3.74	32377	August 22, 1988
2	A	06691	1,1-DCA	3650	5/19/1992	-0.00110	4.20380	66.9	0.00110	0.40178	630.1	1.73	-3635.2	-9.95	30108	June 5, 1982
2		06691	1,1-DCE	7	5/19/1992	-0.00050	3.17550	23.9	0.00050	0.18263	1386.2	3.80	2459.2	6.73	36202	February 11, 1999
. 2	Α	06691	CF	100	5/19/1992	-0.00040	9.98740	21750.7	0.00040	0.14610	1732.8	4.74	13455.6	36.84	47199	March 21, 2029
2	Α	06691	MC	5	5/19/1992	-0.00110	9.54050	13911.9	0.00110	0.40178	630.1	1.73	7210.1	19.74	40953	February 14, 2012
2	Α	06691	TCE	5.	5/19/1992	-0.00008	4.94950	141.1	0.00008	0.02922	8663.8	23.72	41750.8	114.31	75494	September 9, 2106
2	Α	06991	1,1-DCE	7	5/18/1992	-0.00010	-0.24870	0.8	0.00010	0.03653	6931.0	18.98	-21946.1	-60.09	11796	Goal was never exceeded
2		06991	CT	5	5/18/1992	-0.00010	3.04310	21.0	0.00010	0.03653	6931.0	18.98	14336.6	39.25	48079	August 18, 2031
2		0987	MC	5	10/12/1987	-0.00060	2.45040	11.6	0.00060	0.21915	1155.2	3.16	1401.6	3.84	33464	August 13, 1991
2	Α	13191	1,1,1-TCA	200	5/19/1992	-0.00050	2.64820	14.1	0.00050	0.18263	1386.2	3.80	-5300.2	-14.51	28443	November 13, 1977
2	Α	13191	1,1-DCA	3650	5/19/1992	-0.00040	1.51820	4.6	0.00040	0.14610	1732.8	4.74	-16710.7	-45.75	17032	Goal was never exceeded
2	A	13191	CF	100	5/19/1992	-0.00090	6.33730	565.3	0.00090	0.32873	770.1	2.11	1924.6	5.27	35668	August 25, 1997
2		13191	MC	5	5/19/1992	-0.00090	4.66910	106.6	0.00090	0.32873	770.1	2.11	3399.6	9.31	37143	September 8, 2001
2	Α	13191	PCE	5	5/19/1992	-0.00010	4.23030	68.7	0.00010	0.03653	6931.0	18.98	26208.6	71.76	59952	February 19, 2064
2	A	1587	1,1,1-TCA	200	9/10/1987	-0.00010	1.23660	3.4	0.00010	0.03653	6931.0	18.98	-40617.2	-111.20	-8587	Goal was never exceeded
2	Α	1587	1,1-DCE	7	9/10/1987	-0.00004	1.72200	5.6	0.00004	0.01461	17327.5	47.44	-5597.8	-15.33	26432	May 13, 1972
2	Α	1587	CF	100	9/10/1987	-0.00020	3.73040	41.7	0.00020	0.07305	3465.5	9.49	-4373.9	-11.97	27656	September 19, 1975
2	Α	1587	CT	5	9/10/1987	-0.00020	7.98140	2926.0	0.00020	0.07305	3465.5	9.49	31859.8	87.23	63890	December 1, 2074
2	Α	1587	PCE	5	9/10/1987	-0.00030	5.91170	369.3	0.00030	0.10958	2310.3	6.33	14340.9	39.26	46371	December 14, 2026
2	A	1587	TCE	5	9/10/1987	-0.00030	5.23530	187.8	0.00030	0.10958	2310.3	6.33	12086.2	33.09	44116	October 12, 2020
2	A	90299	TCE	5	8/5/1999	-0.00050	1.30020	3.7	0.00050	0.18263	1386.2	3.80	-618.5	-1.69	35759	November 24, 1997
3		0271	1,1-DCE	7	8/27/1986	-0.00120	3.63350	37.8	0.00120	0.43830	577.6	1.58	1406.3	3.85	33057	July 3, 1990
3		0271	CF	100	8/27/1986	-0.00030	5.14180	171.0	0.00030	0.10958	2310.3	6.33	1788.8	4.90	33440	July 20, 1991
3	Α .	0271	PCE	5	8/27/1986	-0.00040	4.51660	91.5	0.00040	0.14610	1732.8	4.74	7267.9	19.90	38919	July 20, 2006
	Α	0271	TCE	5	8/27/1986	-0.00060	9.24540	10356.8	0.00060	0.21915	1155.2	3.16	12726.6	34.84	44378	June 30, 2021
	Α	06791	CF	100	5/20/1992	-0.00140	-0.18480	0.8	0.00140	0.51135	495.1	1.36	-3421.4	-9.37	30323	January 6, 1983
3		06791	CT	5	5/20/1992	-0.00010	1.75770	5.8	0.00010	0.03653	6931.0	18.98	1482.6	4.06	35227	June 10, 1996
	Α	06791	PCE	5	5/20/1992	-0.00160	-0.36230	0.7	0.00160	0.58440	433.2	1.19	-1232.3	-3.37	32512	January 3, 1989
3	Α	07391	1,1,1-TCA	200	3/16/1992	-0.00030	6.14300	465.4	0.00030	0.10958	2310.3	6.33	2815.6	7.71	36495	November 30, 1999
	Α	07391	1,1-DCA	3650	3/16/1992	-0.00060	5.83100	340.7	0.00060	0.21915	1155.2	3.16	-3952.5	-10.82	. 29727	May 20, 1981
3	A	07391	1,1-DCE	7	3/16/1992	-0.00020	5.46350	235.9	0.00020	0.07305	3465.5	9.49	17587.9	48.15	51267	May 10, 2040
	Α	07391	CF	100	3/16/1992	-0.00009	7.45000	1719.9	0.00009	0.03287	7701.1	21.08	31609.2	86.54	65288	September 30, 2078
	Α	07391	cis-1,2-DCE	70	3/16/1992		5.87980	357.7	0.00050	0.18263	1386.2	3.80	3262.6	8.93	36942	February 19, 2001
	Α	07391	CT	5	3/16/1992	-0.00100	7.46280	1742.0	0.00100	0.36525	693.1	1.90	5853.4	16.03	39532	March 25, 2008

				1	* B							· · · · · · · · · · · · · · · · · · ·		ı i	Predicted	
				Tier II	D - C	lnC vs T	lnC	T	1	1	half-life	half-life	decay time	decay time	Date # of	Prodicted Data of Manting
PSA	Flow-	Well#	Chemical	Goal	Reference	Slope (per	Intercept	Intercept	k point	k point			to meet goal	to meet goal		Predicted Date of Meeting
	path			ug/L	Date of Plot	day)	(In units)	(ug/L)	(per day)	(per yr)	(days)	(years)	(days)	(yr)	Meeting	Goal if it continues to decay
		00001	TOF.	<u> </u>	2/16/1992		11 21100	72020.2	0.00009	0.02207	7701.1	21.08	106684.0	292.08	Goal 140363	A 1 10 2204
3		07391	TCE	5	3/16/1992	-0.00009	11.21100	73939.3	0.00009	0.03287 0.14610	1732.8	4.74	-8142.3	-22.29	23894	April 18, 2284 May 31, 1965
3		1187	1,1,1-TCA	200	9/16/1987	-0.00040	2.04140	7.7	0.00040	0.14610	3465.5	9.49	-8142.3 361.4	0.99	32397	September 11, 1988
		1187	1,1-DCE	100	9/16/1987	-0.00020	2.01820				9901.4		-441.0	<del></del>	31595	
		1187	CF	100	9/16/1987	-0.00007	4.57430	97.0	0.00007 0.00010	0.02557	6931.0		-441.0 -16514.0	1———		July 1, 1986 Goal was never exceeded
		1187	cis-1,2-DCE	70	9/16/1987	-0.00010	2.59710	13.4								· · · · · · · · · · · · · · · · · · ·
	A	1187	СТ	5	9/16/1987	-0.00030	6.57000	713.4	0.00030	0.10958	2310.3 23103.3	6.33 63.25	16535.2 67322.1	45.27 184.32	48571 99358	December 23, 2032
	A	1187	PCE .	5	9/16/1987	-0.00003	3.62910	37.7	0.00003	0.01096						January 11, 2172 Goal was never exceeded
		00897	CF	100	9/30/1997	-0.00001	1.10150	3.0	0.00001	0.00365	69310.0	<b>.</b>				
		00897	MC	5	9/30/1997	-0.00170	9.13740	9296.6	0.00170	0.62093	407.7	1.12	4428.2	·	40131	November 14, 2009
		0174	TCE	5	8/26/1986	-0.00010	7.98080	2924.3	0.00010	0.03653	6931.0		63713.6		95364	February 2, 2161
		01791	MC	5	12/19/1991	-0.00320	2.64780	14.1	0.00320	1.16880	216.6		324.5		33915	November 7, 1992
		01791	PCE	5	12/19/1991	-0.00020	2.31940	10.2	0.00020	0.07305	3465.5	9.49	3549.8		37141	September 6, 2001
		02291	1,1,1-TCA	200	12/16/1991	-0.00040	2.31400	10.1	0.00040	0.14610	1732.8	4.74	-7460.8		26127	July 13, 1971
		02291	1,1-DCA	3650	12/16/1991	-0.00020	1.07620	2.9	0.00020	0.07305	3465.5		-35631.4	-97.55		Goal was never exceeded
		02291	1,1-DCE	7	12/16/1991	-0.00020	2.18490	8.9	0.00020	0.07305	3465.5		1194.9		34783	March 24, 1995
		02291	CF	100	12/16/1991	-0.00008	1.35210	3.9	0.00008	0.02922	8663.8	23.72	-40663.4	-111.33		Goal was never exceeded
		02291	CT	5	12/16/1991	-0.00009	-0.56290	0.6	0.00009	0.03287	7701.1	21.08	-24137.1	-66.08		Goal was never exceeded
	Α	12091	МС	5	12/19/1991	-0.00410	2.81520	16.7	0.00410	1.49753	169.0			0.81	33885	October 8, 1992
		15699	1,1,1-TCA	200	3/10/1999	-0.00060	3.08920	22.0	0.00060	0.21915	1155.2			-10.08	32547	February 8, 1989
	Α	15699	1,1-DCE	7	3/10/1999	-0.00010	4.15210	63.6	0.00010	0.03653	6931.0		22061.9	60.40	58291	August 3, 2059
	Α	15699	CF	100	3/10/1999	-0.00100	3.18660	24.2	0.00100	0.36525	693.1	1.90			34810	April 21, 1995
	Α	15699	cis-1,2-DCE	70		-0.00120	5.77880	323.4	0.00120	0.43830	577.6		1275.3	3.49	37504	September 5, 2002
	Α	15699	PCE	5	3/10/1999	-0.00150	6.81560	912.0		0.54788	462.1	<del> </del>	3470.8		39700	September 8, 2008
	Α	15699	TCE	5	-	-0.00170	7.50640	1819.7	0.00170	0.62093	407.7		3468.8	1	39698	September 6, 2008
	Α	1987	PCE	5		-0.00040	6.95520	1048.6		0.14610	1732.8	ļ	13364.4		46379	December 23, 2026
		1987	TCE	5		-0.00040	4.38500	80.2	0.00040	0.14610	1732.8		6938.9		39954	May 20, 2009
		2387	MC	5		-0.00070	1.71330	5.5		0.25568	990.1	2.71	148.4	0.41	32178	February 5, 1988
		4386	CT	5		-0.00005	0.98880	2.7		0.01826	13862.0	<del></del>	-12412.8		19434	March 16, 1953
		02091	CF	100	12/14/1991	-0.00100	-0.85450	0.4	0.00100	0.36525	693.1	1.90			28126	January 1, 1977
		02091	CT	5	12/14/1991	-0.00060	-0.58420	0.6		0.21915	1155.2				29930	December 9, 1981
		03391	1,1,1-TCA	200	12/5/1991	-0.00050	1.51120	4.5	0.00050	0.18263	1386.2				26003	March 10, 1971
		03391	1,1-DCE	7	12/5/1991	-0.00030	1.39710	4.0	0.00030	0.10958	2310.3				31748	December 1, 1986
		03391	CF	100	12/5/1991	-0.00010	2.73940	15.5	0.00010	0.03653	6931.0					Goal was never exceeded
		03391	TCE	5	12/5/1991	-0.00010	4.23840	69.3	0.00010	0.03653	6931.0				59867	November 26, 2063
7	Α	03691	1,1,1-TCA	200	6/8/1992	-0.00030	1.84030	6.3	0.00030		2310.3				22236	November 16, 1960
1	1	03691	1,1-DCE	7	6/8/1992	-0.00040	1.67360	5.3	0.00040	0.14610	1732.8			-1.86	33082	July 28, 1990
7	Α	03691	CF	· 100	6/8/1992	-0.00020		28.5	0.00020	0.07305	3465.5			-17.17	27491	April 7, 1975
7	Α	03691	cis-1,2-DCE	70	6/8/1992	-0.00003	2.36500	10.6	0.00003	0.01096	23103.3	63.25	-62783.2	-171.89	-29020	Goal was never exceeded
7	Α	03691	CT	5	6/8/1992	-0.00020	5.89860	364.5	0.00020	0.07305	3465.5	9.49	21445.8	58.72	55209	February 24, 2051
7	A	03691	TCE	5	6/8/1992	-0.00020	4.01570	55.5	0.00020	0.07305	3465.5	9.49	12031.3	32.94	45794	May 17, 2025
7	Α	0374	1,1,1-TCA	200	8/25/1986			27.8		0.47483	533.2	1.46	-1517.4	-4.15	30132	June 29, 1982
7	Α	0374	1,1-DCE	7		-0.00080	2.42980	11.4	0.00080	0.29220	866.4	2.37	604.9	1.66	32254	April 20, 1988
7	Α	0374	CF	100	8/25/1986	-0.00030	3.04650	21.0	0.00030	0.10958	2310.3	6.33	-5195.6	-14.22	26453	June 3, 1972
7	Α	0374	CT	5	8/25/1986	-0.00060	6.81070	907.5	0.00060	0.21915	1155.2	3.16	8668.8	23.73	40318	May 19, 2010

					į											,
				Tier II	Ī	lnC vs T	lnC						decay time	decay time	Predicted	·
PSA	Flow-	Well#	Chemical	Goal	Reference	Slope (per	Intercept	Intercept	k point	k point	half-life	half-life		to meet goal	Date # of	Predicted Date of Meeting
FSA	path	Well #	Chemical	ug/L	Date of Plot	day)	(In units)	(ug/L)	(per day)	(per yr)	(days)	(years)	(days)	(yr)	Meeting	Goal if it continues to decay
				ug/L	Ĺ	(day)	(III units)						(uays)	(31)	Goal	
7	A	0374	PCE	5	8/25/1986	-0.00100	5.88660	360.2	0.00100	0.36525	693.1	1.90	4277.2	11.71	35926	May 11, 1998
7	A	0374	TCE	5	8/25/1986	-0.00100	5.44180	230.9	0.00100	0.36525	693.1	1.90	3832.4	10.49	35481	February 20, 1997
7	A	11891	1,1,1-TCA	200	12/19/1991	-0.00020	1.25580	3.5	0.00020	0.07305	3465.5	9.49	-20212.6	-55.34	13378	Goal was never exceeded
7	A	11891	1,1-DCE	7	12/19/1991	-0.00010	1.17820	3.2	0.00010	0.03653	6931.0	18.98	-7677.1	-21.02	25914	December 11, 1970
7	A	11891	CF	100	12/19/1991	-0.00004	2.67790	14.6	0.00004	0.01461	17327.5	47.44	-48181.8	-131.91	-14591	Goal was never exceeded
7	A	11891	TCE	5	12/19/1991	-0.00020	4.17350	64.9	0.00020	0.07305	3465.5	9.49	12820.3	35.10	46411	January 24, 2027
7	A	12191	1,1,1-TCA	200	3/16/1992	-0.00050	2.01830	7.5	0.00050	0.18263	1386.2	3.80	-6560.0	-17.96	27119	March 30, 1974
7		12191	1,1-DCE	7	3/16/1992	-0.00020	1.63460	5.1	0.00020	0.07305	3465.5	9.49	-1556.6	-4.26	32122	December 11, 1987
7	A	12191	CF	100	3/16/1992	-0.00010	2.07020	7.9	0.00010	0.03653	6931.0	18.98	-25349.7	-69.40	8329	Goal was never exceeded
7		12191	CT	5	3/16/1992	-0.00004	5.27430	195.3	0.00004	0.01461	17327.5	47.44	91621.6	250.85	125301	January 21, 2243
7	A	12191	TCE	5	3/16/1992	-0.00006	3.71120	40.9	0.00006	0.02192	11551.7	31.63	35029.4	95.91	68708	February 10, 2088
7		2487	PCE	5	6/7/1990	-0.00010	1.01760	2.8	0.00010	0.03653	6931.0	18.98	-5918.4	-16.20	27113	March 24, 1974
7		2587	CF	100	9/10/1987	-0.00010	1.32890	3.8	0.00010	0.03653	6931.0	18.98	-32762.7	-89.70	-733	Goal was never exceeded
7		2587	CT	5	9/10/1987	-0.00004	4.51370	91.3	0.00004	0.01461	17327.5	47.44	72606.6	198.79	104637	June 24, 2186
7		2587	MC	5	9/10/1987	-0.00020	2.36040	10.6	0.00020	0.07305	3465.5	9.49	3754.8	10.28	35785	December 20, 1997
7		2587	PCE	5	9/10/1987	-0.00020	5.84100	344.1	0.00020	0.07305	3465.5	9.49	21157.8	57.93	53188	August 13, 2045
7		2587	TCE	5	9/10/1987	-0.00030	4.45590	86.1	0.00030	0.10958	2310.3	6.33	9488.2	25.98	41518	September 1, 2013
10		40499	1.1-DCA	3650	11/9/1999	-0.00230	-1.18530	0.3	0.00230	0.84008	301.3	0.83	-4081.6	-11.17	32391	September 5, 1988
10		40499	cis-1,2-DCE	70	11/9/1999	-0.00130	2.09760	8.1	0.00130	0.47483	533.2	1.46	-1654.5	-4.53	34818	April 29, 1995
10		40499	PCE	5	11/9/1999	-0.00120	2.46310	11.7	0.00120	0.43830	577.6	1.58	711.4	1.95	37184	October 20, 2001
10		40499	TCE	5	11/9/1999	-0.00120	0.99980	2.7	0.00120	0.43830	577.6	1.58	-508.0		35965	June 18, 1998
10	Α	41299	1,1-DCA	3650	11/9/1999	-0.00130	1.16890	3.2	0.00130	0.47483	533.2	1.46	-5410.4	-14.81	31063	January 15, 1985
10		41299	1,1-DCE	7	11/9/1999	-0.00120	2.76650	15.9	0.00120	0.43830	577.6	1.58	683.8	1.87	37157	September 22, 2001
10		41299	cis-1.2-DCE	70	11/9/1999	-0.00110	4.29040	73.0	0.00110	0.40178	630.1	1.73	38.1	0.10	36511	December 17, 1999
10		41299	PCE	5	11/9/1999	-0.00070	5.90130	365.5	0.00070	0.25568	990.1	2.71	6131.2	16.79	42604	August 22, 2016
10		41299	TCE	5	11/9/1999		4.02820	56.2	0.00080	0.29220	866.4	2.37	3023.5	8.28	39496	February 18, 2008
10		P416889	1,1,1-TCA	200	11/23/1993	-0.00050	-0.12970	0.9	0.00050	0.18263	1386.2	3.80	-10856.0	-29.72	23440	March 3, 1964
10		P416889	1,1-DCA	3650	11/23/1993	-0.00020	0.10360	1.1	0.00020	0.07305	3465.5	9.49	-40494.4	-110.87	-6198	Goal was never exceeded
10		P416889	1.1-DCE	7	11/23/1993	-0.00030	1.43220	4.2		0.10958	2310.3	6.33	-1712.4	-4.69	32584	March 16, 1989
10		P416889	cis-1,2-DCE	70	11/23/1993	-0.00030	2.12850	8.4	0.00030	0.10958	2310.3	6.33	-7066.7	-19.35	27229	July 19, 1974
10			PCE	5	11/23/1993	-0.00003	3.80150	44.8	0.00003	0.01096	23103.3	63.25	73068.7	200.05	107365	December 12, 2193
10			TCE	5	11/23/1993		1.18760	3.3	0.00001	0.00183	138620.0		-84367.6			Goal was never exceeded
10		P419689	1,1,1-TCA	200	11/19/1993	-0.00080	-0.25730	0.8	0.00080	0.29220	866.4	2.37	-6944.5	-19.01	27347	November 14, 1974
10		P419689	1,1-DCA	3650	11/19/1993	-0.00040	1.60920	5.0		0.14610	1732.8	4.74	-16483.2	-45.13		Goal was never exceeded
10		P419689	1,1-DCE	7	11/19/1993	-0.00040	0.99730	2.7	0.00040	0.14610	1732.8	4.74	-2371.5		31920	
10		P419689	CF	100	11/19/1993	-0.00003	-0.26540	0.8	0.00003	0.01096	23103.3	63.25	<del> </del>			Goal was never exceeded
10		P419689	cis-1,2-DCE	70		-0.00009	2.10880	8.2	0.00009	0.03287	7701.1	21.08	-23774.4			Goal was never exceeded
10		P419689	PCE	5	1	-0.00010	3.22750	25.2	0.00010	0.03653	6931.0		16180.6		50473	March 8, 2038
10		P419689	TCE	5		-0.00010	1.03730	2.8		0.07305	3465.5	9.49	-2860.7	-7.83	31431	January 19, 1986
12		1986	I,1-DCA	3650	9/18/1986		1.31820	3.7		0.18263	1386.2	3.80				Goal was never exceeded
12		1986	cis-1,2-DCE	70			1.01440	2.8		0.18203	1155.2				26283	December 15, 1971
12		1986	MC	5		<del>i</del>	2.15460	8.6		0.21915	1155.2				32582	
12		1986	trans-1,2-DCE	70			1.63040	5.1		0.36525	693.1	1.90		-7.17	29055	July 18, 1979
12		21298	CF	100	9/22/1998	<del>i</del>	1.94180	7.0		0.30323	17327.5		<del></del>			Goal was never exceeded
	А	121270	101	100	31441 1990	-0.00004	1.57100	7.0	0.00004	0.01701	11321.3	77,47	1 -00304.3	1 -102.30	-30324	Goar was never exceeded

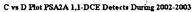
PSA	Flow- path	Well #	Chemical	Tier II Goal ug/L	Reference Date of Plot	InC vs T Slope (per day)	InC Intercept (In units)	Intercept (ug/L)	k point (per day)	k point (per yr)	half-life (days)	half-life (years)	decay time to meet goal (days)	(ут)	Predicted Date # of Meeting Goal	Predicted Date of Meeting Goal if it continues to decay
12	Α	21298	СТ	5	9/22/1998	-0.00003	2.40700	11.1	0.00003	0.01096	23103.3	63.25	26585.4	72.79	62645	July 6, 2071
12	A	21598	TCE	5	9/23/1998	-0.00010	4.44580	85.3	0.00010	0.03653	6931.0	18.98	28363.6	77.66	64425	May 19, 2076
12	A	21798	1,1-DCA	3650	9/15/1998	-0.00050	1.99650	7.4	0.00050	0.18263	1386.2	3.80	-12412.0	-33.98	23641	September 21, 1964
12	A	21798	cis-1,2-DCE	70	9/15/1998	-0.00008	2.47280	11.9	0.00008	0.02922	8663.8	23.72	-22196.2	-60.77	13857	Goal was never exceeded
12	A	21898	1,1-DCA	3650	9/22/1998	-0.00020	-0.01920	1.0	0.00020	0.07305	3465.5	9.49	-41108.4	-112.55	-5048	Goal was never exceeded
12	A	84702	1,1,1-TCA	200	4/9/2002	-0.00380	2.99190	19.9	0.00380	1.38795	182.4	0.50	-607.0	-1.66	36748	August 10, 2000
12	A	84702	1,1-DCA	3650	4/9/2002	-0.00190	4.19050	66.1	0.00190	0.69398	364.8	1.00	-2111.6	-5.78	35243	June 27, 1996
12	A	84702	1,1-DCE	7	4/9/2002	-0.00370	4.74980	115.6	0.00370	1.35143	187.3	0.51	757.8	2.07	38113	May 5, 2004
12	Α	84702	CF	100	4/9/2002	-0.00110	-0.39010	· 0.7	0.00110	0.40178	630.1	1.73	-4541.2	-12.43	32814	November 1, 1989
12	Α	84702	chloroethane	29.4	4/9/2002	-0.00270	1.76300	5.8	0.00270	0.98618	256.7	0.70	-599.3	-1.64	36756	August 17, 2000
12	A	84702	cis-1,2-DCE	70	4/9/2002	-0.00250	2.49660	12.1	0.00250	0.91313	277.2	0.76	-700.8	1.92	36654	May 8, 2000
12	A	84702	PCE	5	4/9/2002	-0.00370	6.03630	418.3	0.00370	1.35143	187.3	0.51	1196.4	3.28	38551	July 18, 2005
12	Α	84702	TCE	5	4/9/2002	-0.00330	4.55400	95.0	0.00330	1.20533	210.0	0.58	892.3	2.44	38247	September 17, 2004
12		P114789	CF	100	11/22/1993	-0.00030	-0.45600	0.6	0.00030	0.10958	2310.3	6.33	-16870.6	-46.19	17424	Goal was never exceeded
12	Α	P114789	cis-1,2-DCE	70	11/22/1993	-0.00030	2.24680	9.5	0.00030	0.10958	2310.3	6.33	-6672.3	-18.27	27623	August 16, 1975
12	A	P114789	MC	5	11/22/1993	-0.00030	-0.08520	0.9	0.00030	0.10958	2310.3	6.33	-5648.8	-15.47	28646	June 5, 1978
12	A	P114789	TCE	5	11/22/1993	-0.00040	1.45990	4.3	0.00040	0.14610	1732.8	4.74	-373.8	-1.02	33921	November 13, 1992
14			MC	5	3/17/1999	-0.00220	6.44050	626.7	0.00220	0.80355	315.0	0.86	2195.9	6.01	38432	March 20, 2005
14	Α		TCE	5	3/17/1999	-0.00007	1.31650	3.7	0.00007	0.02557	9901.4	27.11	-4184.8	-11.46	32051	October 1, 1987
14	Α	18499	MC	5	3/17/1999	-0.00110	6.07670	435.6	0.00110	0.40178	630.1	1.73	4061.1	11.12	40297	April 29, 2010
14	Α		PCE	5	3/17/1999	-0.00020	4.76230	117.0	0.00020	0.07305	3465.5	9.49	15764.3	43.16	52000	May 14, 2042
14	Α	18599	CF	100	3/2/1999	-0.00130	7.88550	2658.5	0.00130	0.47483	533.2	1.46	2523.3	6.91	38744	January 27, 2006
14	A	18599	СТ	5	3/2/1999	-0.00070	9.57770	14439.2	0.00070	0.25568	990.1	2.71	11383.2	31.17	47604	May 1, 2030
14	A	18699	1,1-DCA	3650	3/17/1999	-0.00110	0.38630	1.5	0.00110	0.40178	630.1	1.73	-7105.6	-19.45	29130	October 2, 1979
14	Α	18799	1,1-DCA	3650	3/17/1999	-0.00110	1.20430	3.3	0.00110	0.40178	630.1	1.73	-6362.0	-17.42	29874	October 15, 1981
14	Α		CF	100	3/17/1999	-0.00001	6.27120	529.1	0.00001	0.00365	69310.0	189.76	166603.0	456.13	202839	May 7, 2455
14	Α	18799	MC	5	3/17/1999	-0.00210	3.32060	27.7	0.00210	0.76703	330.0	0.90	814.8	2.23	37051	June 8, 2001
14	Α		CF	100	9/22/1998	-0.00020	4.39670	81.2	0.00020	0.07305	3465.5	9.49	-1042.4	-2.85	35018	November 14, 1995
14	Α		MC	5	9/22/1998	-0.00230	2.66720	14.4	0.00230	0.84008	301.3	0.83	459.9	1.26	36520	December 25, 1999
14	Α		CT	5	11/11/2002	-0.00340	8.00060	2982.7	0.00340	1.24185	203.9	0.56	1879.8	5.15	39451	January 3, 2008
14	A		PCE	5	11/11/2002	-0.00010	0.94560	2.6	0.00010	0.03653	6931.0	18.98	-6638.4	-18.17	30933	September 7, 1984
14			CF	100	9/22/1998		6.08630	439.8		0.21915	1155.2	3.16	2468.5	6.76	38529	June 25, 2005
14			CT	5	9/22/1998	1	7.37430	1594.5		0.00026	990142.9		8235517.3	22547.62		Millenia from now
14			CF	100		-0.00020	0.03180	1.0		0.07305	3465.5	9.49	-22866.9	-62.61	12598	Goal was never exceeded
		771FD	<del>                                     </del>	170			•									
14		1	PCE	5	3/26/1999	-0.00070	2.37960	10.8	0.00070	0.25568	990.1	2.71	1100.2	3.01	37345	March 30, 2002
14			cis-1,2-DCE	70		-0.00010	-0.44500	0.6		0.03653	6931.0		-46935.0	-128.50	-12885	Goal was never exceeded

	Α	В	С	D	Е	F	G	Н	1	Т	K.	L
<del> </del>	A			ע	L	1	<u> </u>	11	1	,	K	<u>_</u>
1	PSA	Flow- path	Well#	Chemical	Tier II Goal ug/L	Reference Date of Plot	InC vs T Slope (per day)	InC Intercept (In units)	Intercept (ug/L)	k point (per day)	k point (per yr)	half-life (days)
2	2	Α	00491	1,1-DCA	3650	33592	-0.00001	-1.1691	=EXP(H2)	=G2*(-1)	=J2*365.25	=0.6931/J2
3	2	A	00491	1,1-DCE	7	33592	-0.0001	-0.6121	=EXP(H3)	=G3*(-1)	=J3*365.25	=0.6931/J3
4	2	A	00491	CF	100	33592	-0.0002	4.5208	=EXP(H4)	=G4*(-1)	=J4*365.25	=0.6931/J4
5	2	Α	00491	cis-1,2-DCE	70	33592	-0.0002	2.7804	=EXP(H5)	=G5*(-1)	=J5*365.25	=0.6931/J5
6	2	A	00491	CT	5	33592	-0.0003	5.4812	=EXP(H6)	=G6*(-1)	=J6*365.25	=0.6931/J6
7	2	A	00491	PCE	5	33592	-0.0001	3.5132	=EXP(H7)	=G7*(-1)	=J7*365.25	=0.6931/J7
8	2	Α	00491	TCE	5	33592	-0.0002	4.6191	=EXP(H8)	=G8*(-1)	=J8*365.25	=0.6931/J8
9	2	A	01291	CF	100	33745	-0.00003	3.1534	=EXP(H9)	=G9*(-1)	=J9*365.25	=0.6931/J9
10	2	A	06591	CF	100	33743	-0.0005	4.1313	=EXP(H10)	=G10*(-1)	=J10*365.25	=0.6931/J10
11	2	A	06591	CT	5	33743	-0.0002	5.0371	=EXP(H11)	=G11*(-1)	=J11*365.25	=0.6931/J11
12	2	Α	06691	1,1,1-TCA	200	33743	-0.0007	4.3424	=EXP(H12)	=G12*(-1)	=J12*365.25	=0.6931/J12

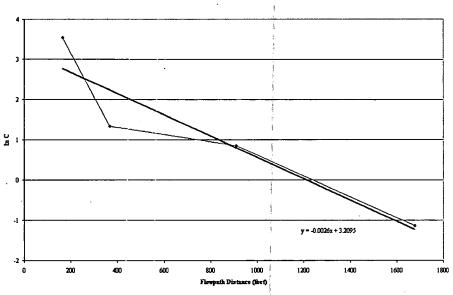
	M	Ň	0	P	Q
1	half-life (years)	decay time to meet goal (days)	decay time to meet goal (yr)	Predicted Date # of Meeting Goal	Predicted Date of Meeting Goal if CAH Continues to Decay
2	=0.6931/K2	=(-1)*LN(E2/I2)/J2	=(-1)*LN(E2/I2)/K2	=F2+N2	=IF(P2<18264,"Goal was never exceeded",P2)
3	=0.6931/K3	=(-1)*LN(E3/I3)/J3	=(-1)*LN(E3/I3)/K3	=F3+N3	=IF(P3<18264,"Goal was never exceeded",P3)
4	=0.6931/K4	=(-1)*LN(E4/I4)/J4	=(-1)*LN(E4/I4)/K4	=F4+N4	=IF(P4<18264,"Goal was never exceeded",P4)
5	=0.6931/K5	=(-1)*LN(E5/I5)/J5	=(-1)*LN(E5/I5)/K5	=F5+N5	=IF(P5<18264,"Goal was never exceeded",P5)
6	=0.6931/K6	=(-1)*LN(E6/I6)/J6	=(-1)*LN(E6/I6)/K6	=F6+N6	=IF(P6<18264,"Goal was never exceeded",P6)
7	=0.6931/K7	=(-1)*LN(E7/I7)/J7	=(-1)*LN(E7/I7)/K7	=F7+N7	=IF(P7<18264,"Goal was never exceeded",P7)
8	=0.6931/K8	=(-1)*LN(E8/I8)/J8	=(-1)*LN(E8/I8)/K8	=F8+N8	=IF(P8<18264,"Goal was never exceeded",P8)
9	=0.6931/K9	=(-1)*LN(E9/I9)/J9	=(-1)*LN(E9/I9)/K9	=F9+N9	=IF(P9<18264,"Goal was never exceeded",P9)
10	=0.6931/K10	=(-1)*LN(E10/I10)/J10	=(-1)*LN(E10/I10)/K10	=F10+N10	=IF(P10<18264,"Goal was never exceeded",P10)
11	=0.6931/K11	=(-1)*LN(E11/I11)/J11	=(-1)*LN(E11/I11)/K11	=F11+N11	=IF(P11<18264,"Goal was never exceeded",P11)
12	=0.6931/K12	=(-1)*LN(E12/I12)/J12	=(-1)*LN(E12/I12)/K12	=F12+N12	=IF(P12<18264,"Goal was never exceeded",P12)

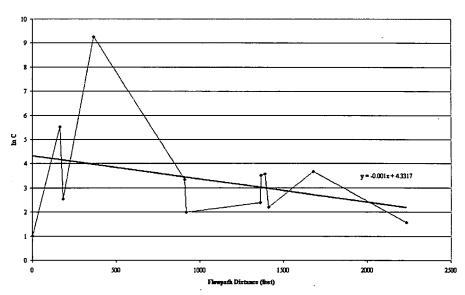
## APPENDIX C

# NATURAL LOG CONCENTRATION VERSUS FLOWPATH DISTANCE PLOTS FOR VARIOUS TIME PERIODS



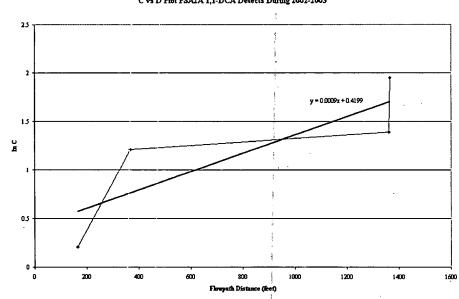
#### C vs D Plot PSA2A Chloroform Detects During 2002-2003

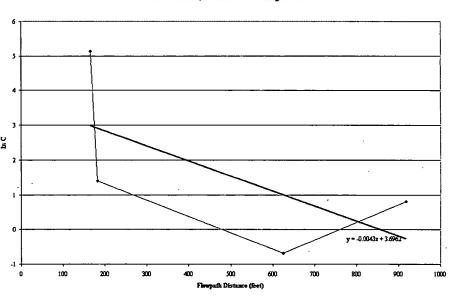


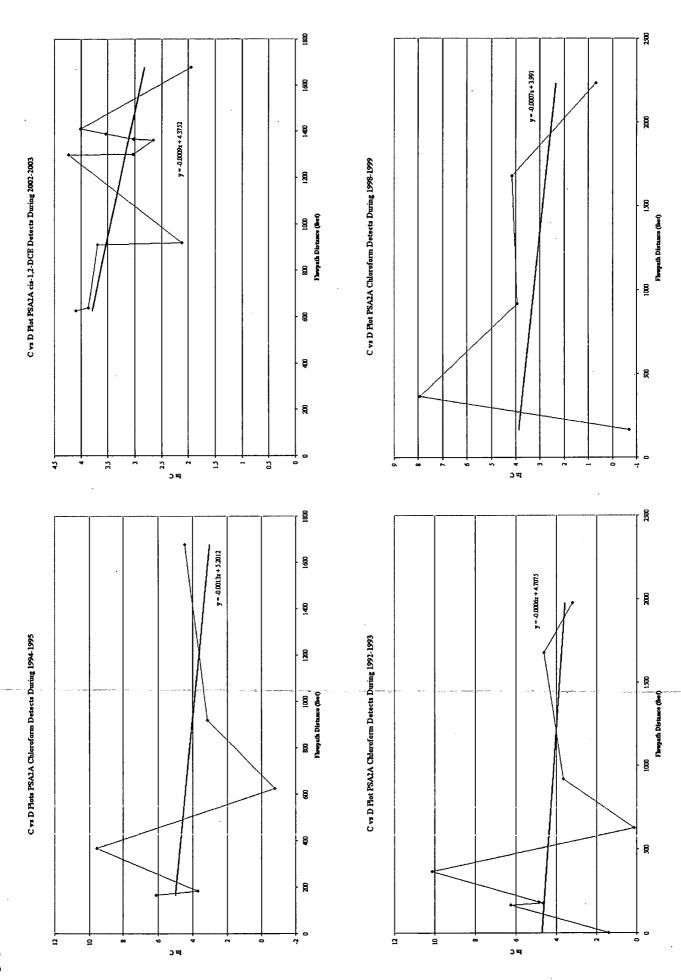


### C vs D Flot PSA2A 1,1-DCA Detects During 2002-2003

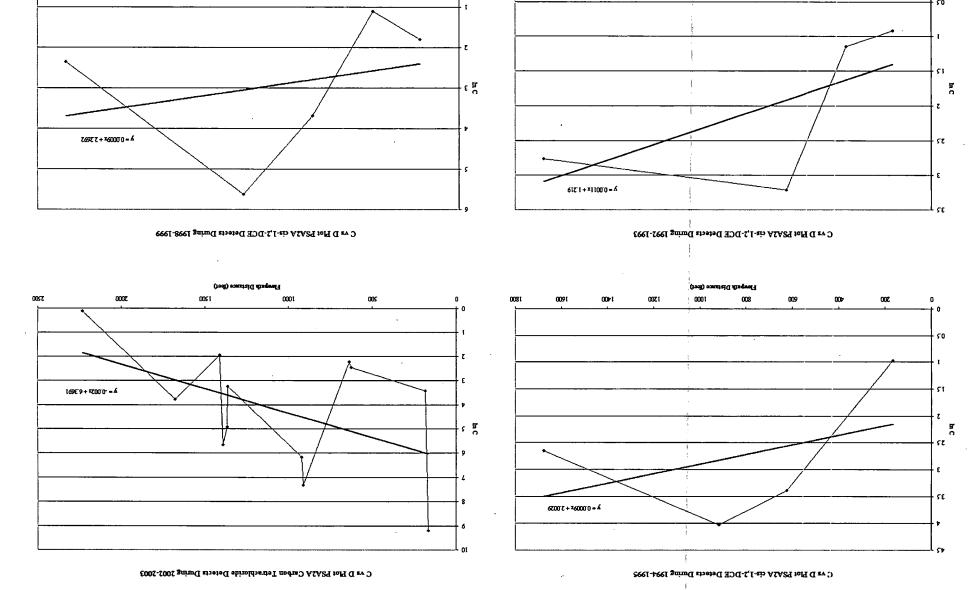
C vs D Plot PSA2A 1,1-DCE Detects During 1994-1995







300



1900

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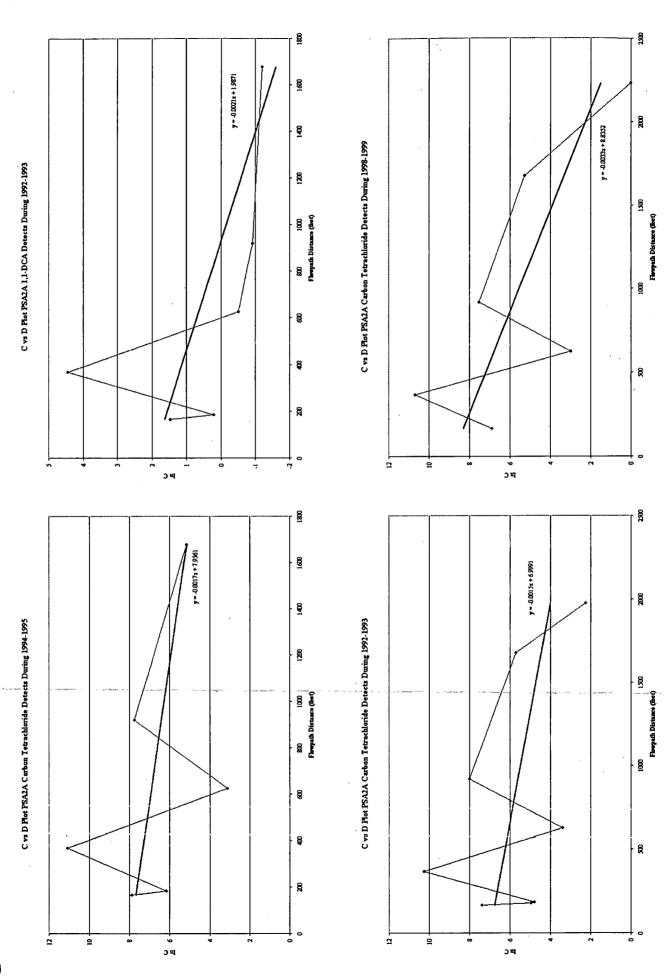
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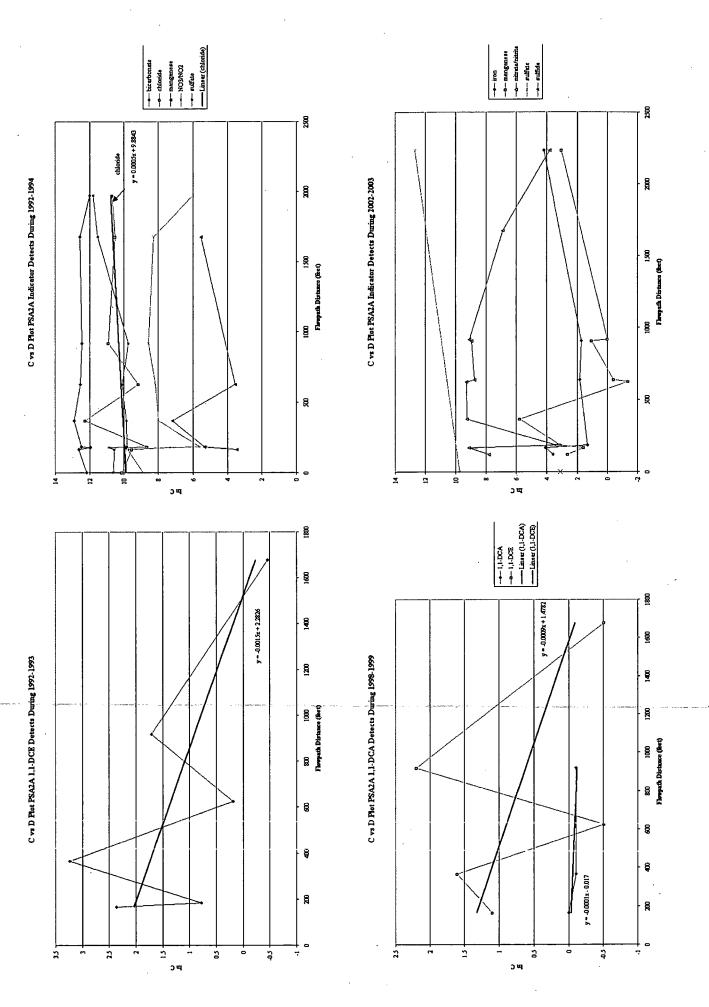
1800

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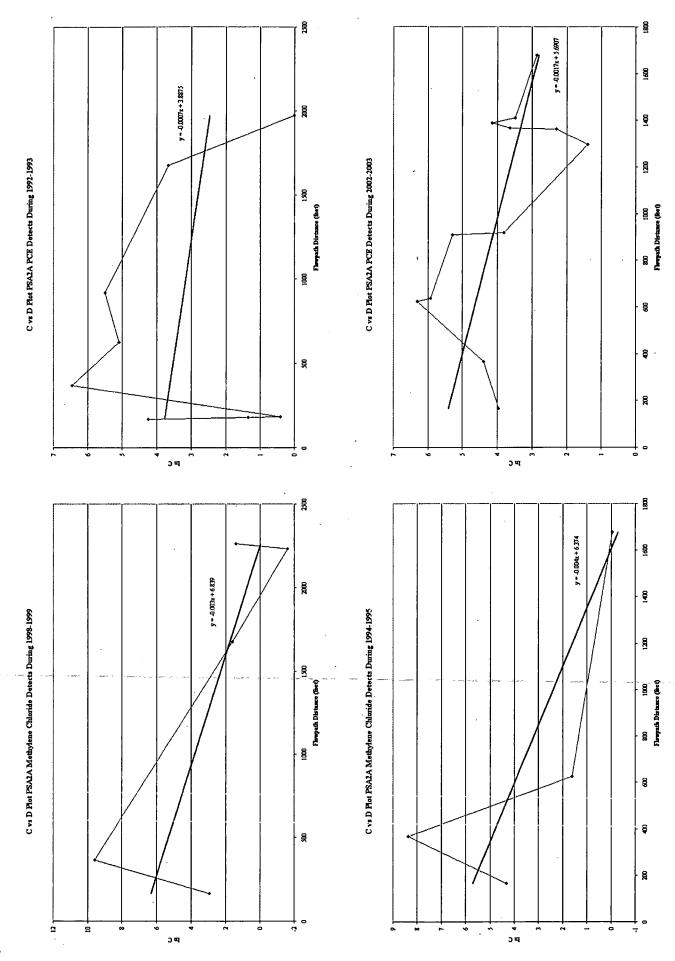


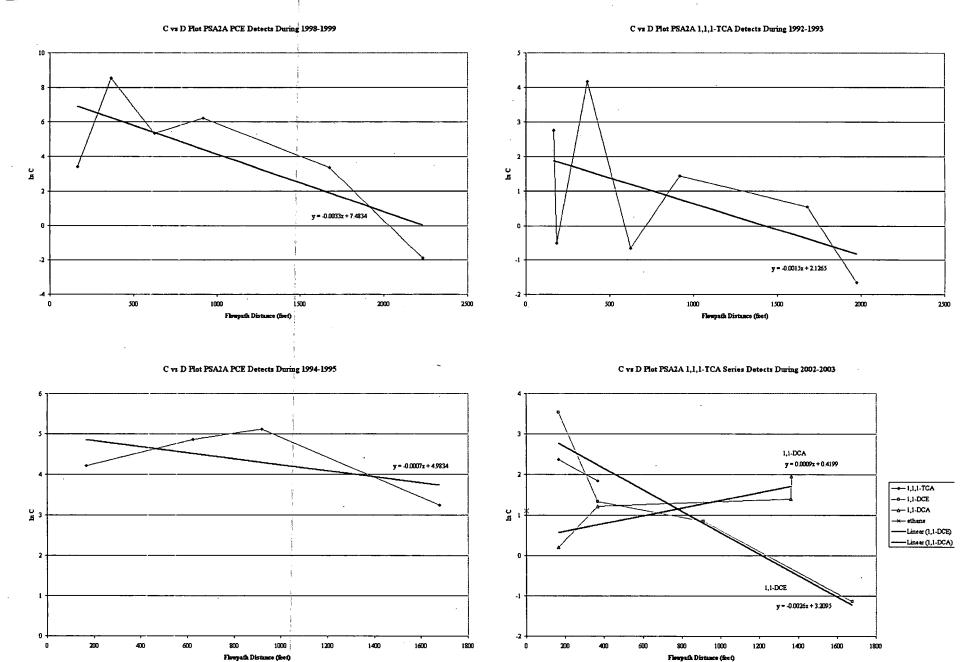


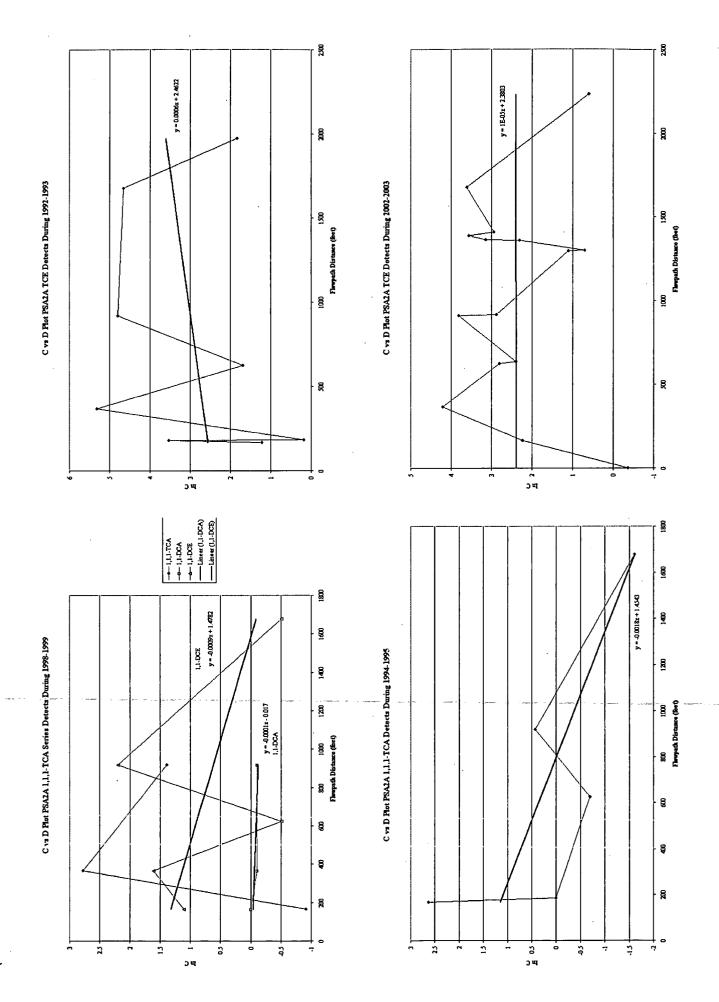
1800 0091 1400 1300 1000 300 3200 3000 000 —Linear (chloride) OOI etsilus -ZON/EON --D E --- mengenese epuorus --AMMORIAN — 72.5 + x100.0 = V y = 0.0008x + 9.4351 C vs D Flot PSA2A Methylene Chloride Detects During 1990-1991 C vs D Flot PSAAA Indicator Detects During 1994-1995 (test) sousteid shaqeeff (bed) sonatried disqualf 3200 2000 0005 7200 0002 A = -0.006x + 12.252 999E++200000--4 20 5 C vs D Flot PSALA Methylene Chloride Detects During 1992-1993 C vs D Hot PSALA Methylene Chloride Detects During 2000-2001

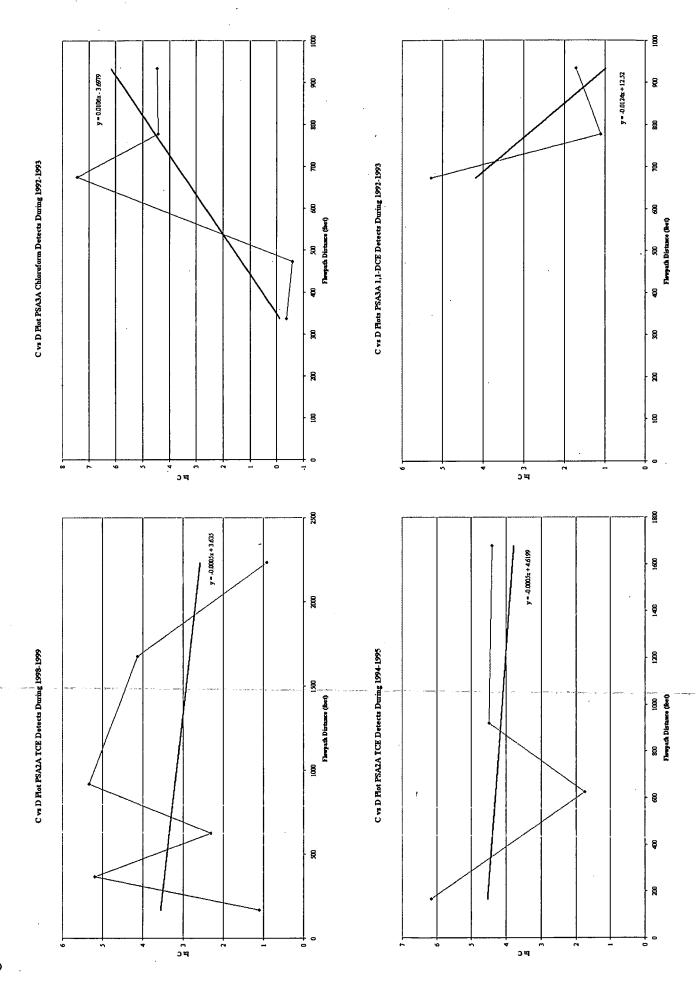
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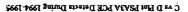


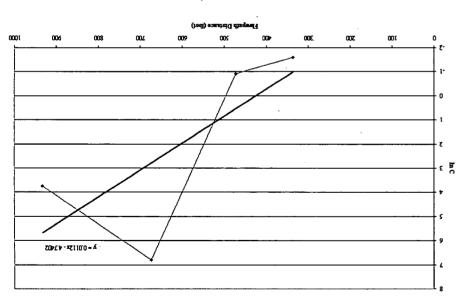


8 chlonde y = 0.0013x + 10.925 8 8 C vs D Plet PSA3A Indicator Detects During 1994-1995 C vs D Plot PSA3A Indicator Detects During 1992-1993 thloride y = -0.0003x + 11.815 8 矣 8 8 8 o m m 8 y=0.0103x-3.0996 y=0.0113x - 3.1795 暴 C vs D Flot PSA3A Carbon Tetrachloride Detects During 1992-1993 C vs D Hot PSA3A Chloreform Detects During 1994-1995 ) SOO 64 Flowpath Distance (Seet) S00 Flowpath Distance (Set) 8 8 8 54

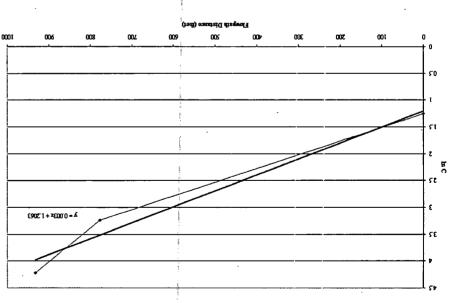
317

85

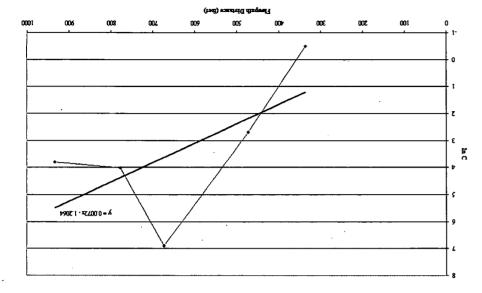




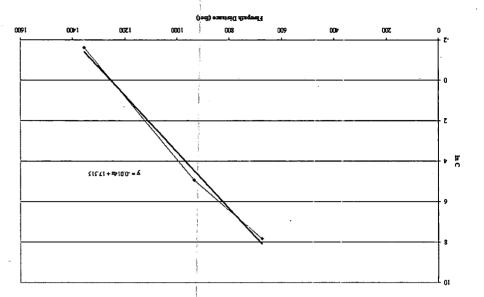
### C vs D Flot PSA3A Methylene Chloride Detects During 1990-1991

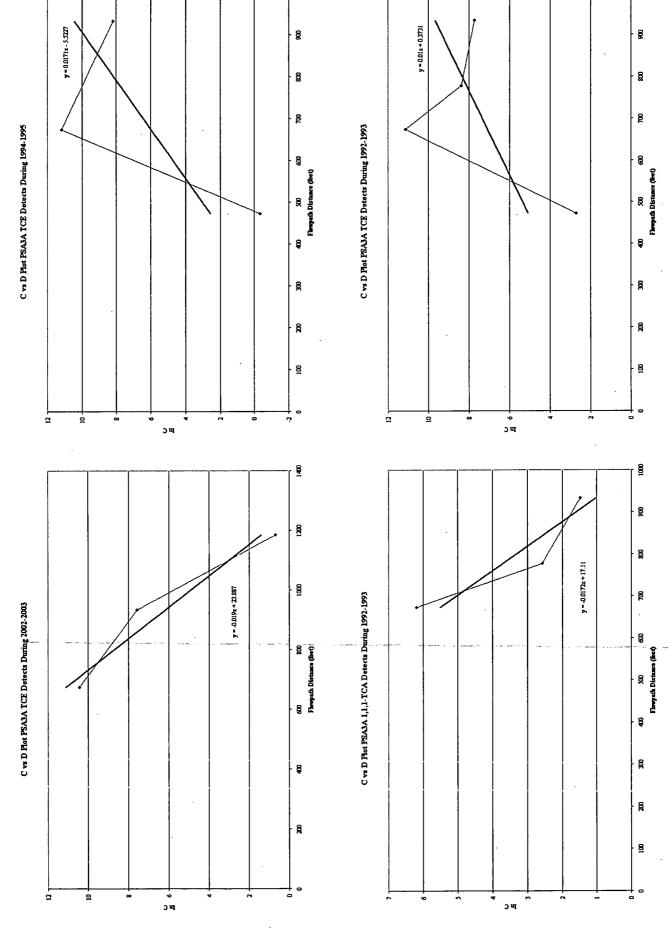


#### C vs D Flot PSA3A PCE Detects During 1992-1993



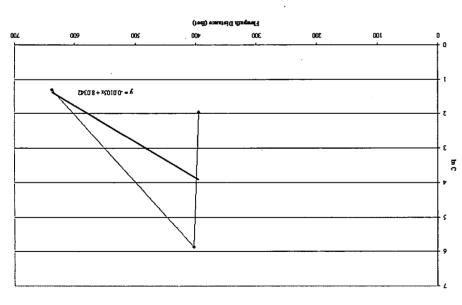
#### C vs D Not PSA3A Methylene Chloride Detects During 2000-2001

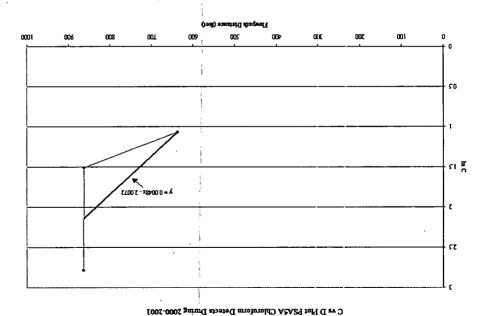




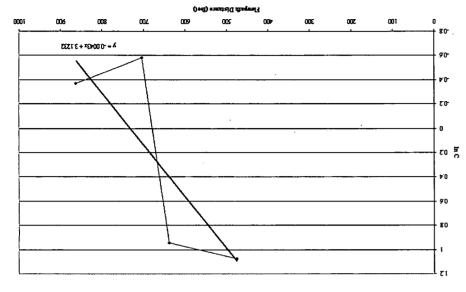
3/9

C vs D Flot PSASA Chloroform Detects During 1992-1993

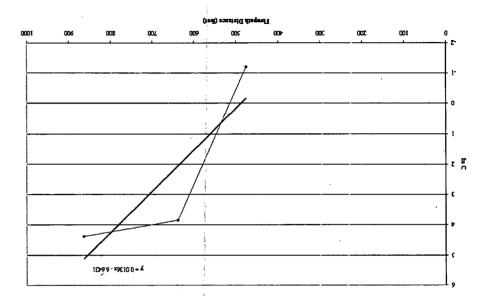


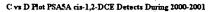


C vs D Hot PSASA Chloroform Detects During 2002-2003

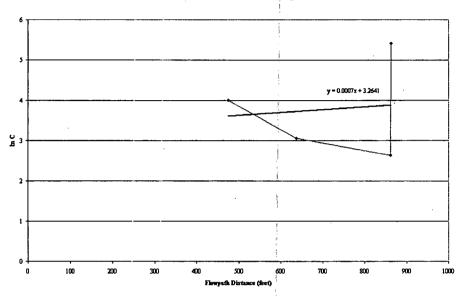


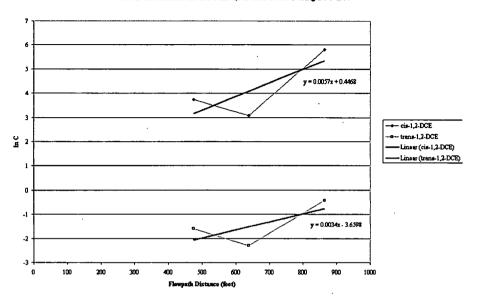
C vs D Ffot PSASA I, I-DCE Detects During 1998-1999





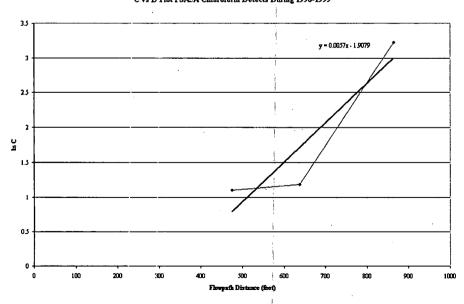
#### C vs D Plot PSA5A cis and trans 1,2-DCE Detects During 1998-1999

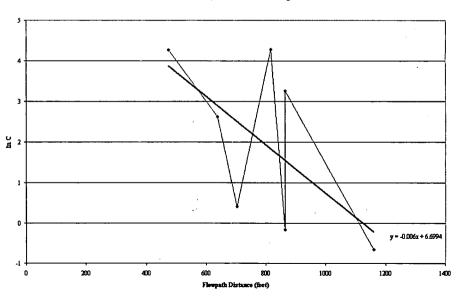


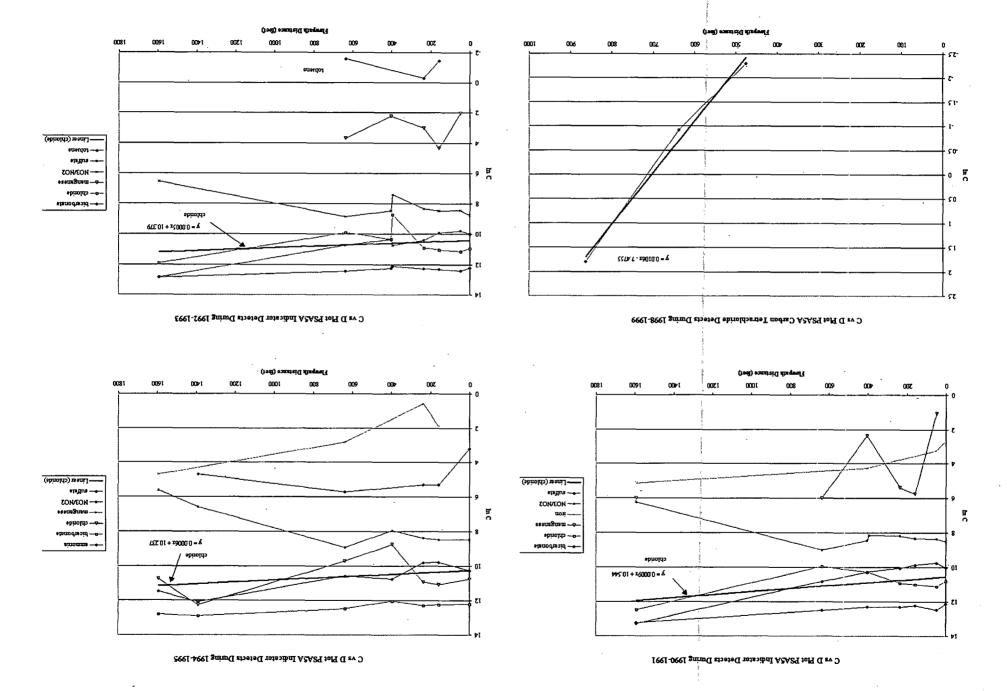


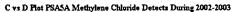
C vs D Flot PSASA Chloroform Detects During 1998-1999

C vs D Plot PSA5A cis-1,2-DCE Detects During 2002-2003

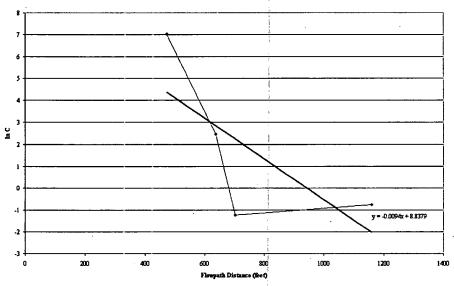




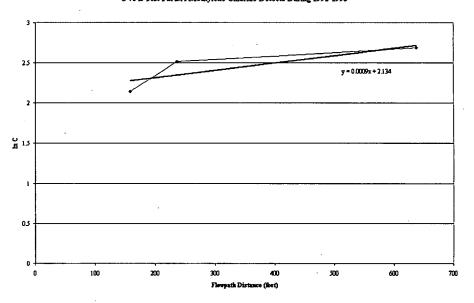




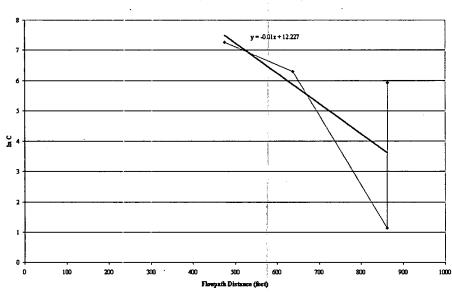




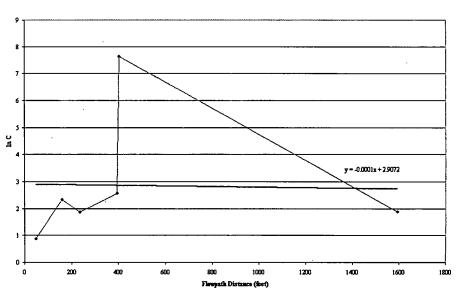
#### C vs D Plot PSA5A Methylene Chloride Detects During 1992-1993



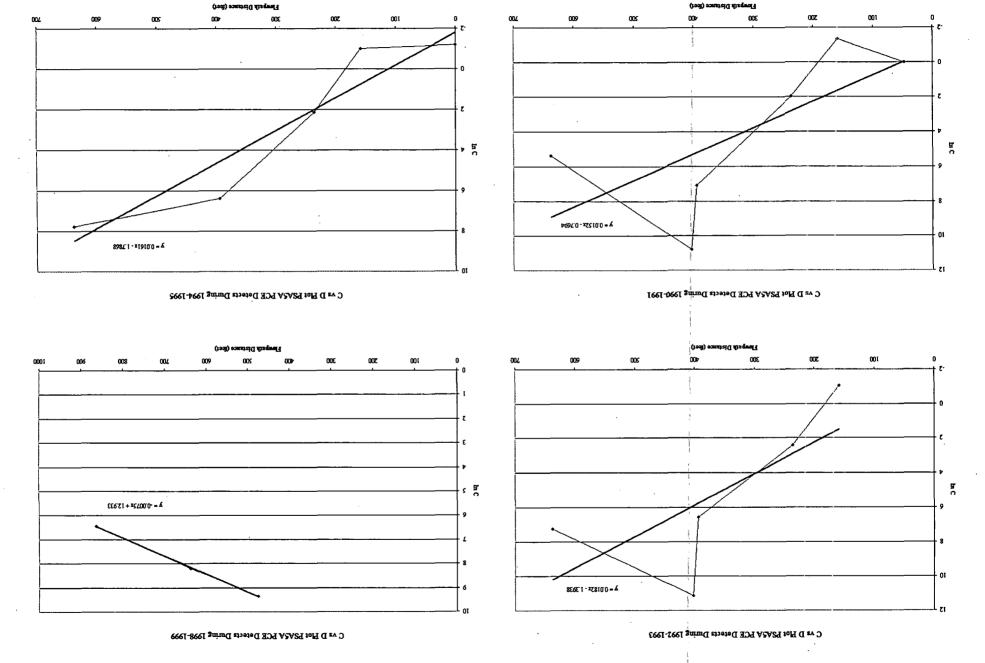
C vs D Flot PSA5A Methylene Chloride Detects During 2000-2001

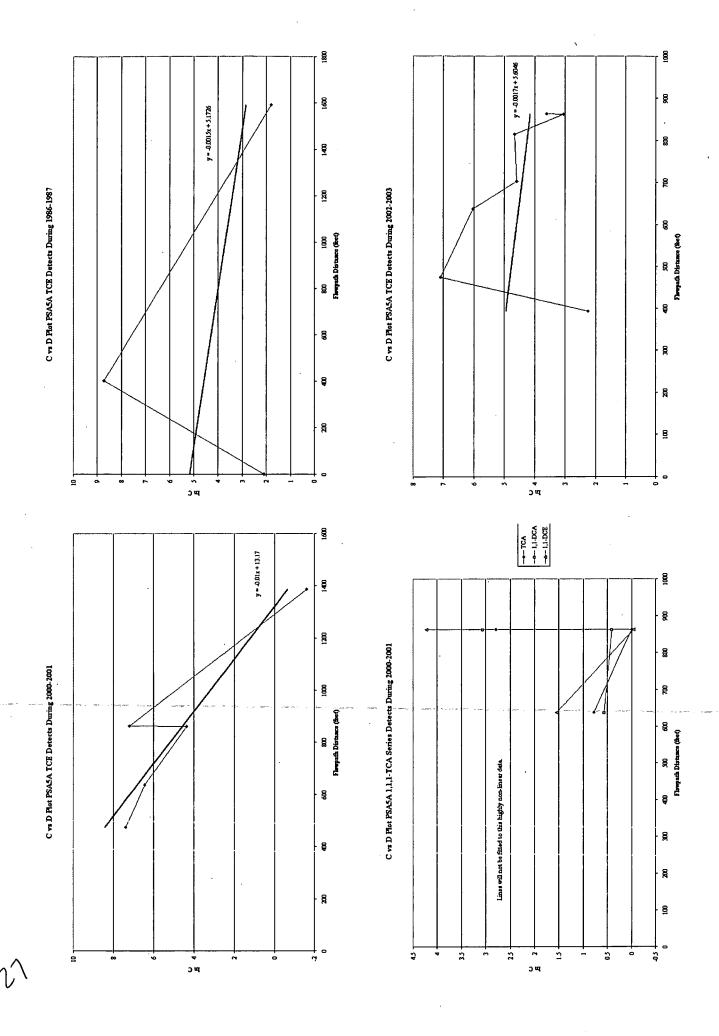


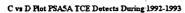
C vs D Flot PSA5A Methylene Chloride Detects During 1990-1991

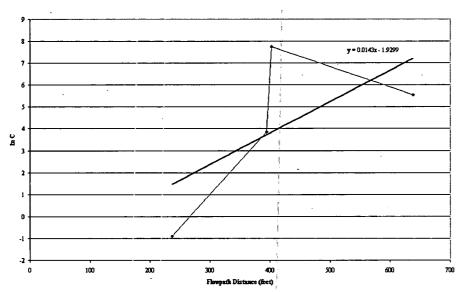


륁 C vs D Plot PSASA PCE Detects During 2002-2003 C vs D Hot PSA5A PCE Detects During 2000-2001 y = -0.0123x + 15.942 State of the Section (Sect) 500 ( Floreparth Distance (Sect) A lins will not be fitted to this highly non-linear date. ρc ъщ 22 8 98 ā y = -0.0063x + 10.68 8 C vs D Flot PSASA Methylene Chloride Detects During 1994-1995 C vs D Flot FSASA Methylene Chloride Detects During 1998-1999 120 No kine has been fitted to this highly nonlinear data. 800 Floreparth Distance (feet) 800 1000 Flowparth Distance (See f) 8

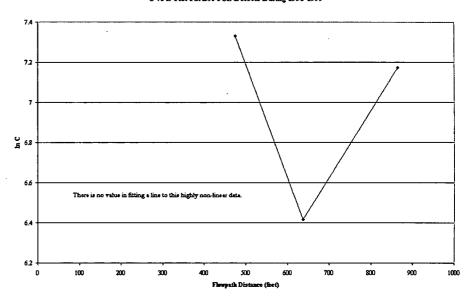




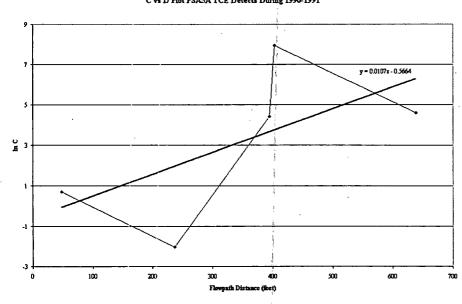




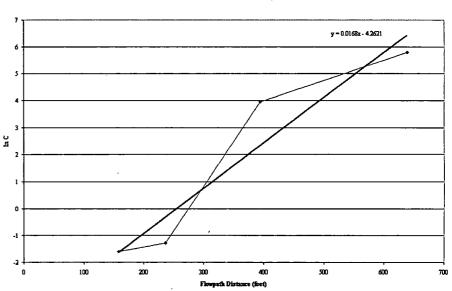
#### C vs D Plot PSA5A TCE Detects During 1998-1999

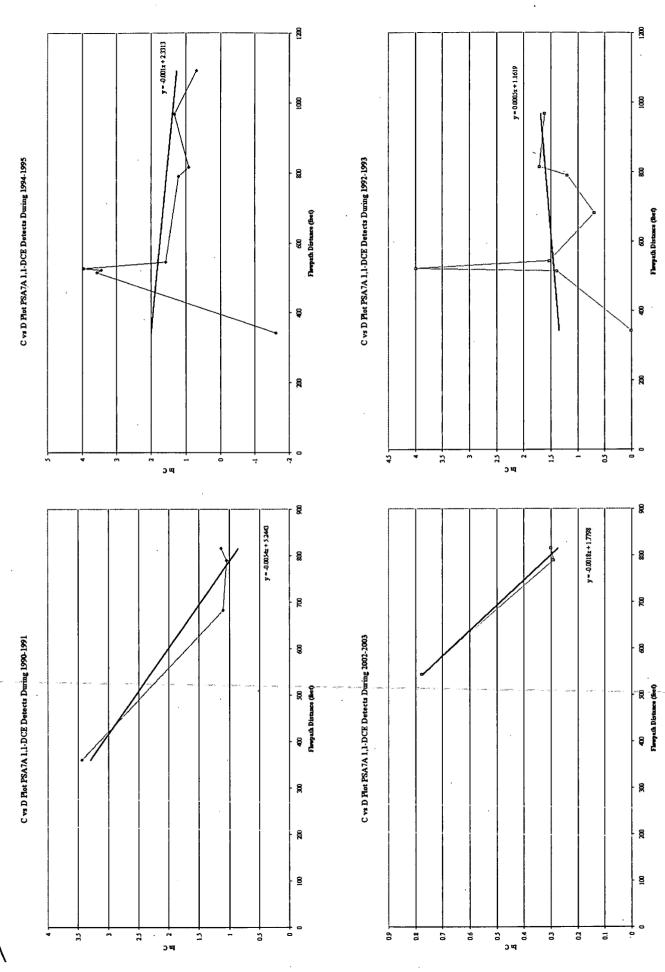


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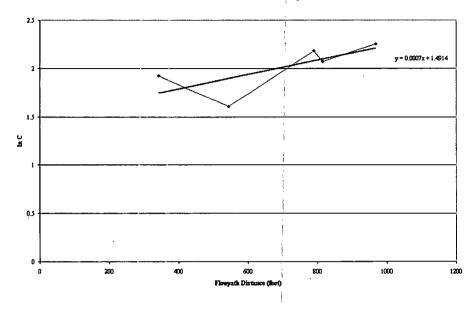
C vs D Plot PSASA TCE Detects During 1994-1995



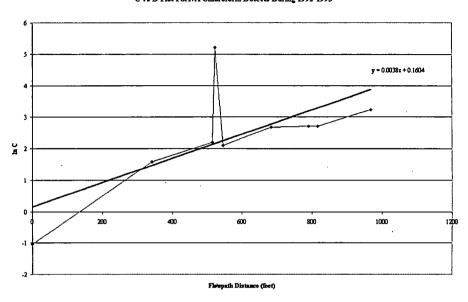




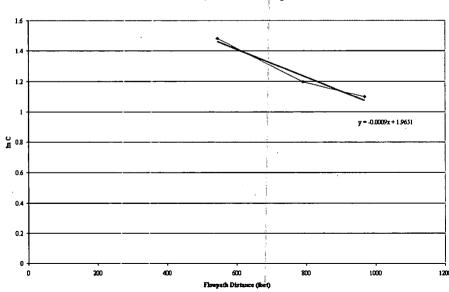
#### C vs D Plot PSA7A Chloroform Detects During 2002-2003



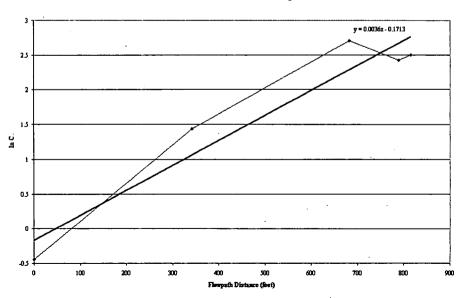
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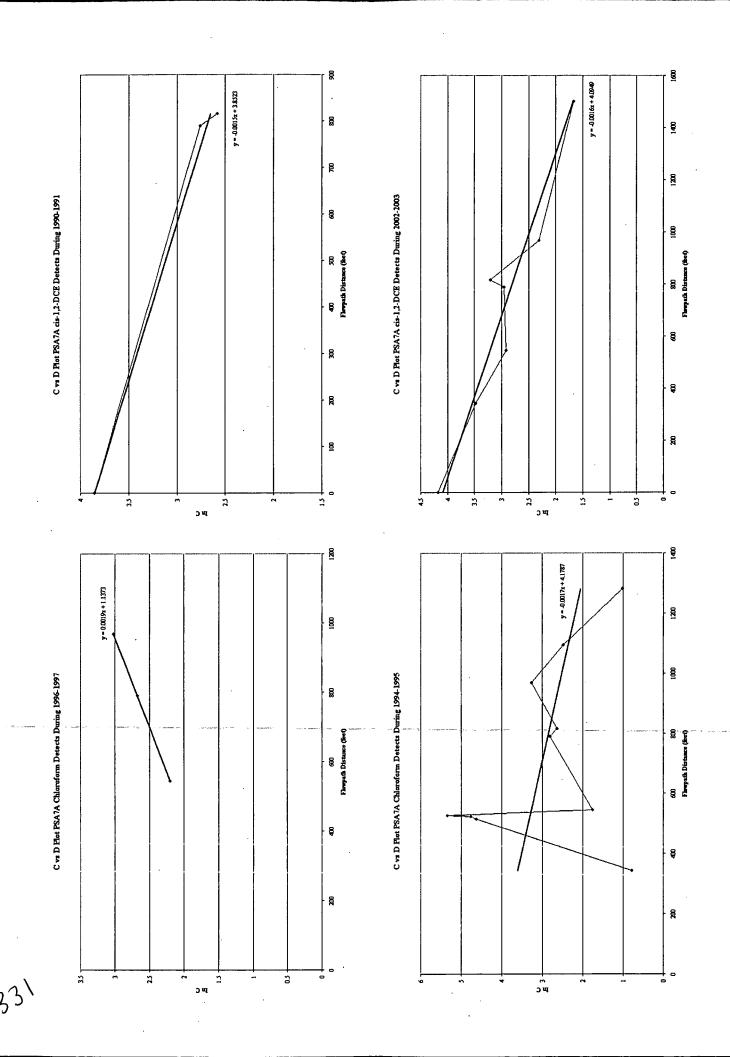


C vs D Plot PSA7A 1,1-DCE Detects During 1996-1997

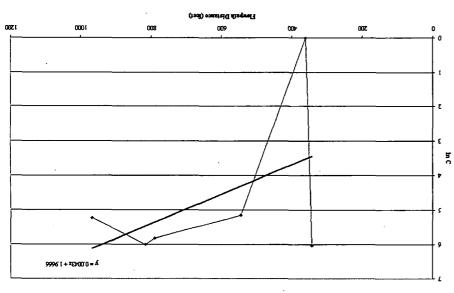


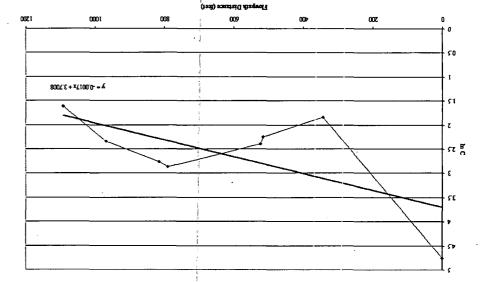
C vs D Flot PSA7A Chloroform Detects During 1990-1991





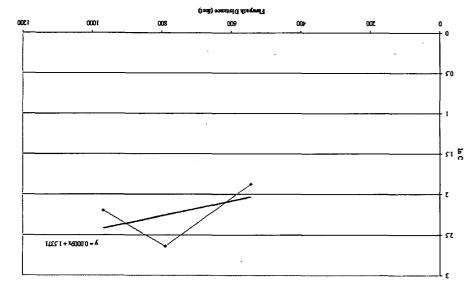
C vx D Flot PSA7A Carbon Tetrachloride Detects During 2002-2003



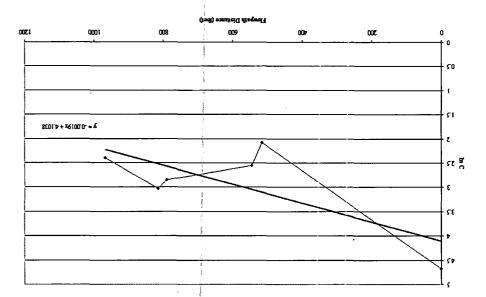


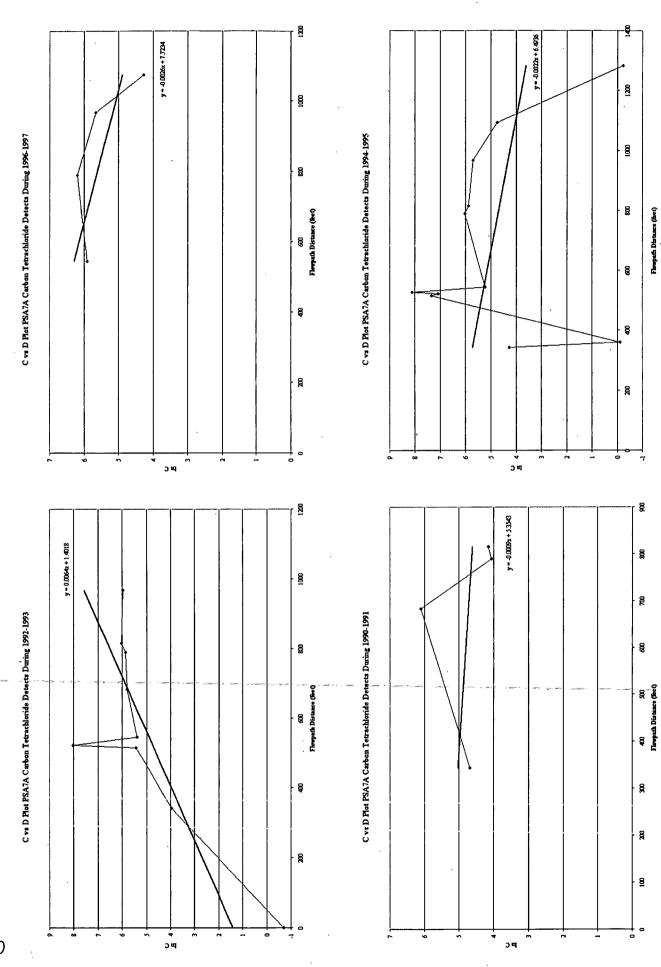
C vs D Plot PSA7A cis-1,2-DCE Detects During 1994-1995

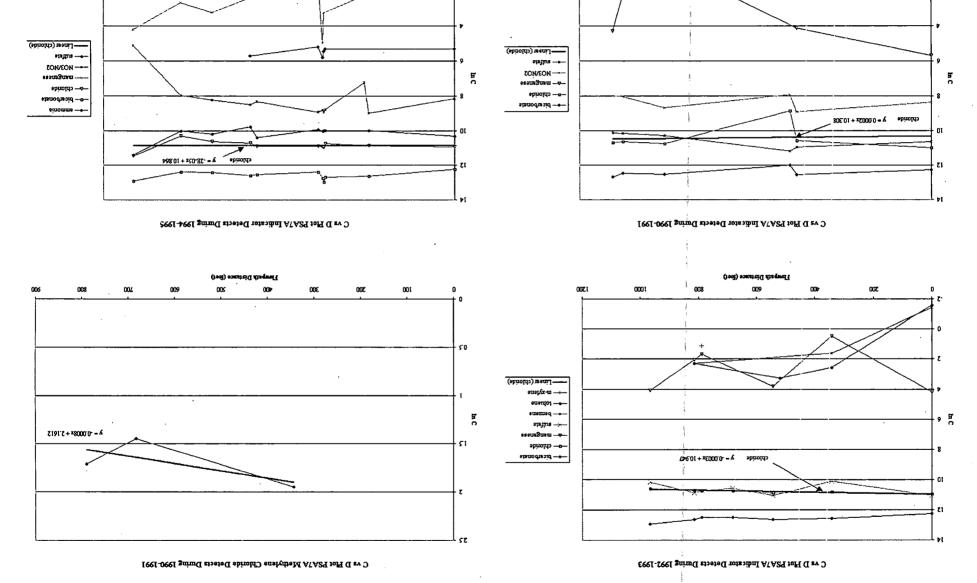
C vs D Mot PSA7A cis-1,2-DCE Detects During 1996-1997



C vs D Flot PSA7A cis-1,2-DCE Detects During 1992-1993



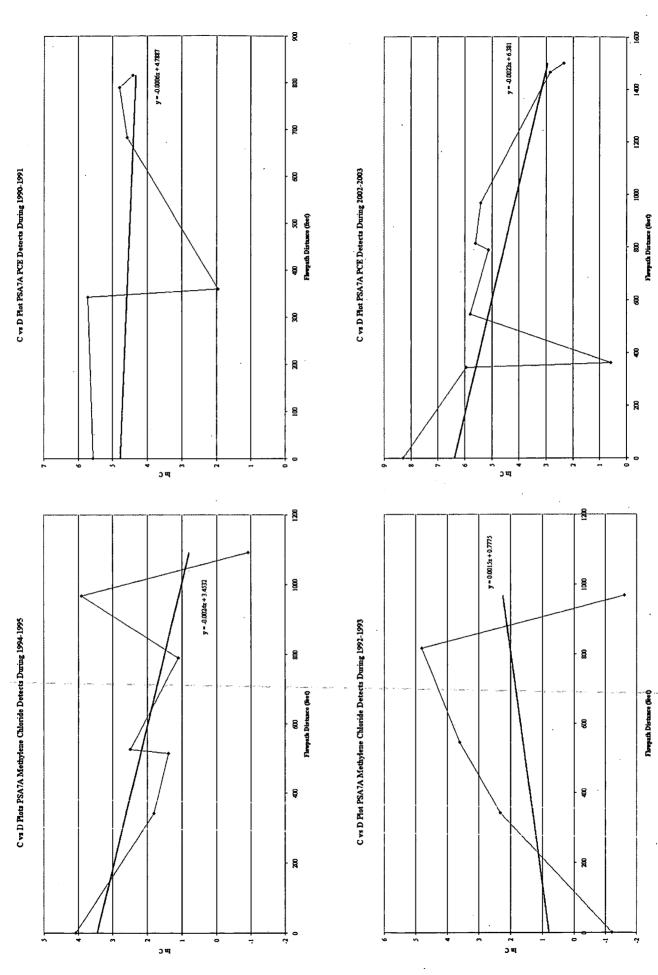




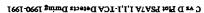
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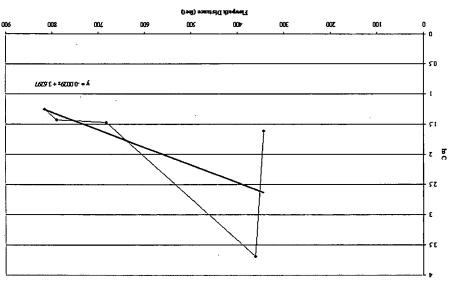
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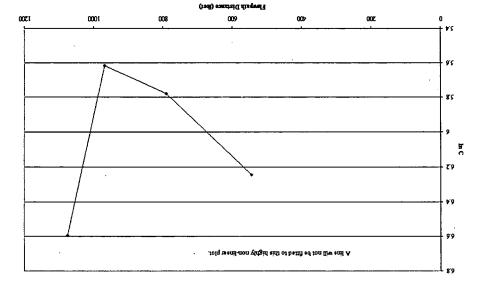


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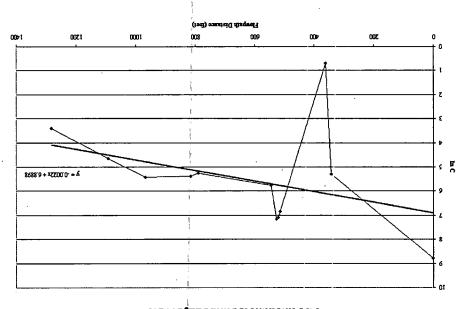




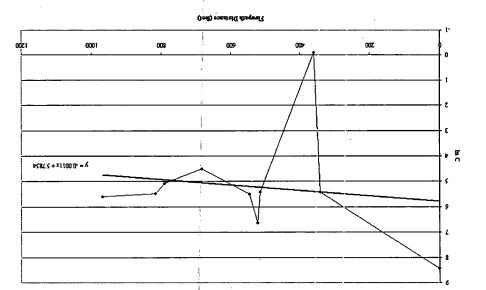
C vs D Flot PSA7A PCE Detects During 1996-1997

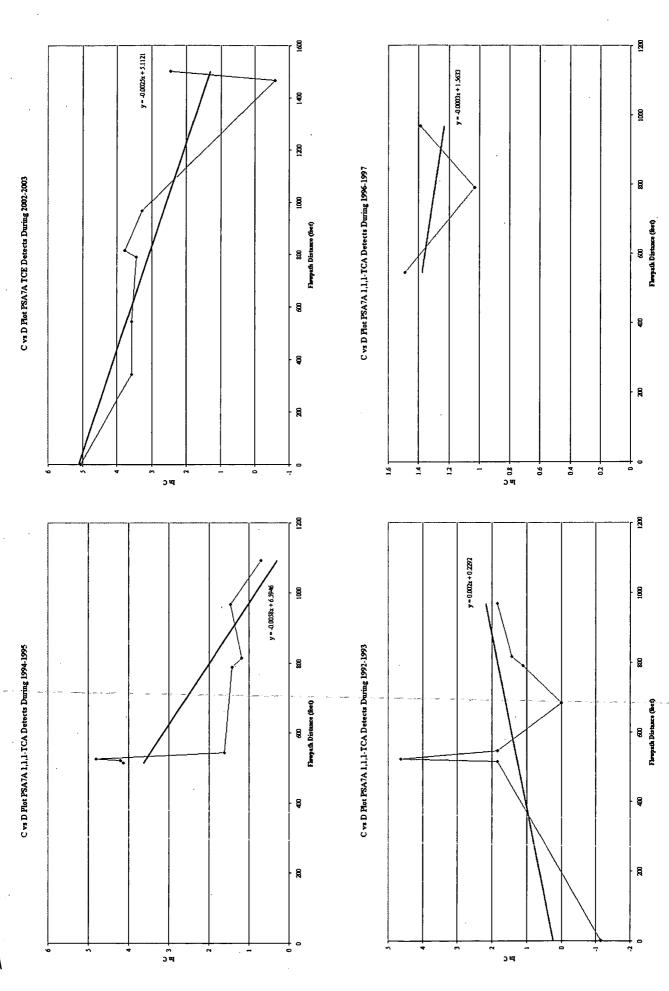


C vs D Hot PSA'A PCE Detects During 1994-1995

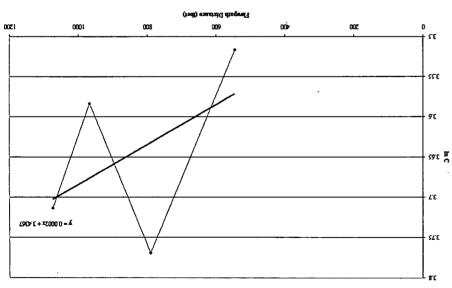


C vs D Hot PSA7A PCE Detects During 1992-1993

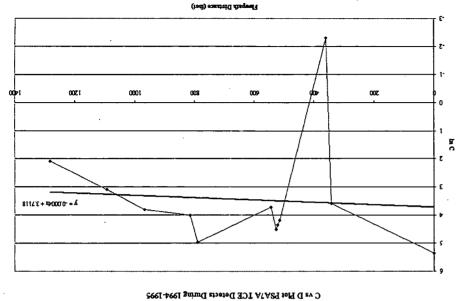




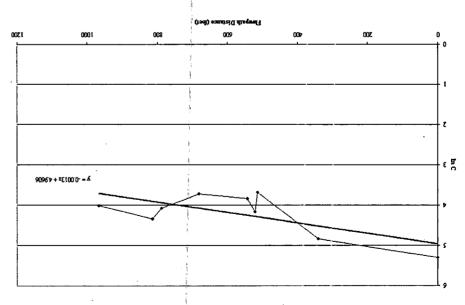




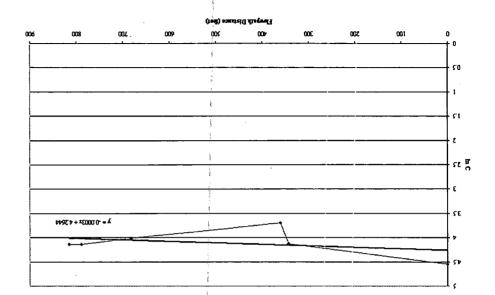
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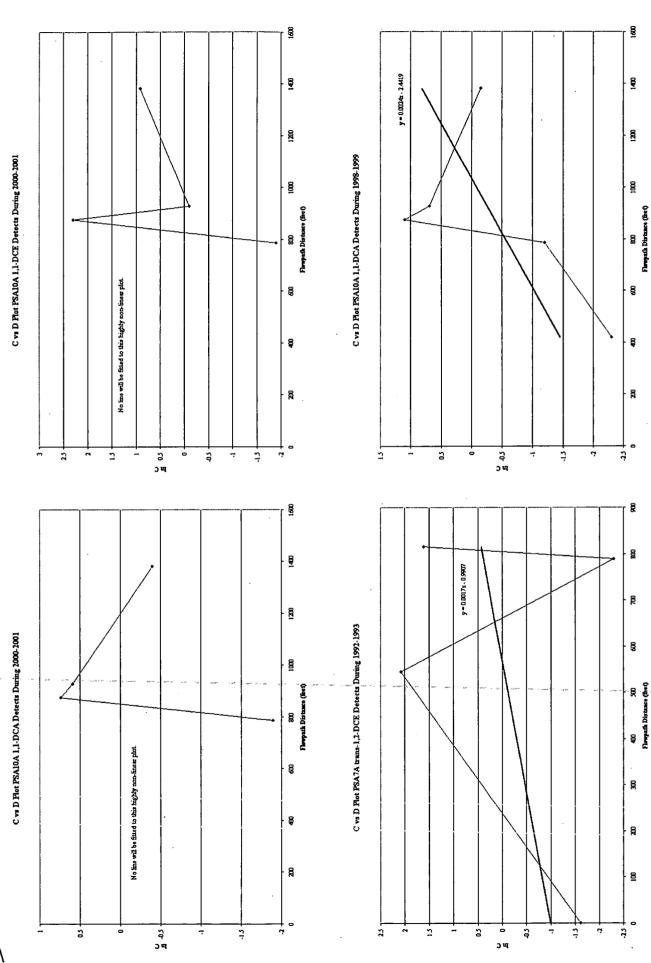


C 42 D Hot ESA7A TCE Detects During 1992-1993

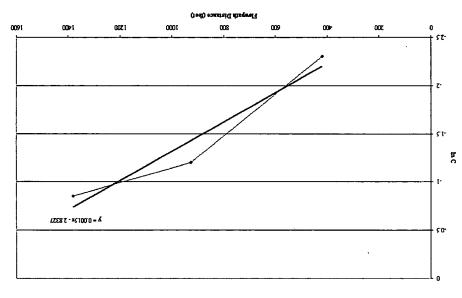


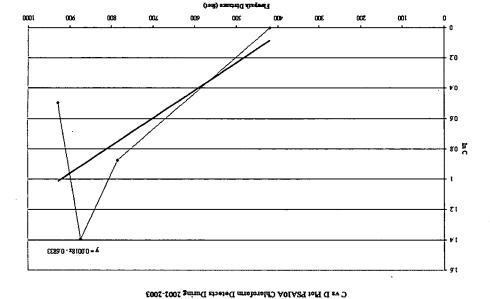
C vs D Mot PSA7A TCE Detects During 1990-1991



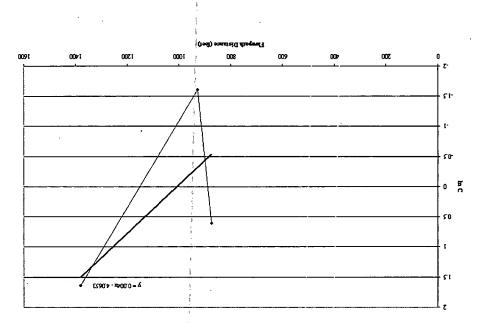


C vs D Hot PSA10A Chloroform Detects During 1998-1999

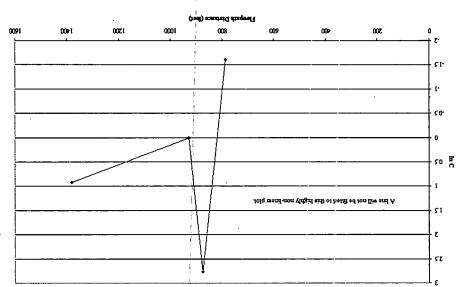


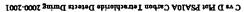


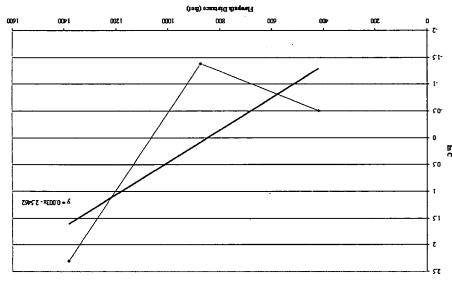
C vs D Flot PSA10A Chloroform Detects During 2000-2001

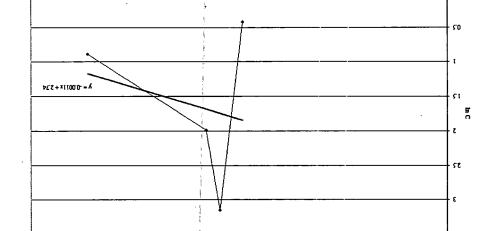


C vs D Flot PSA10A 1,1-DCE Detects During 1998-1999



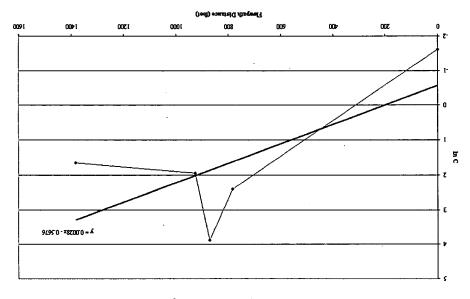






C vs D Hot PSA10A cis-1,2-DCE Detects During 2002-2003

C vs D Flot PSA10A cis-1,2-DCE Detects During 1998-1999

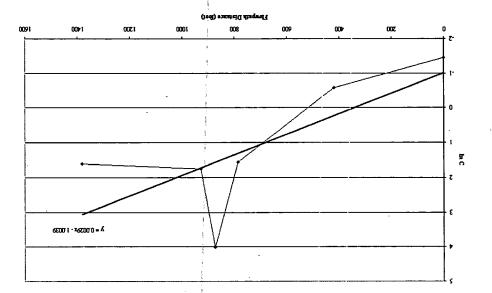


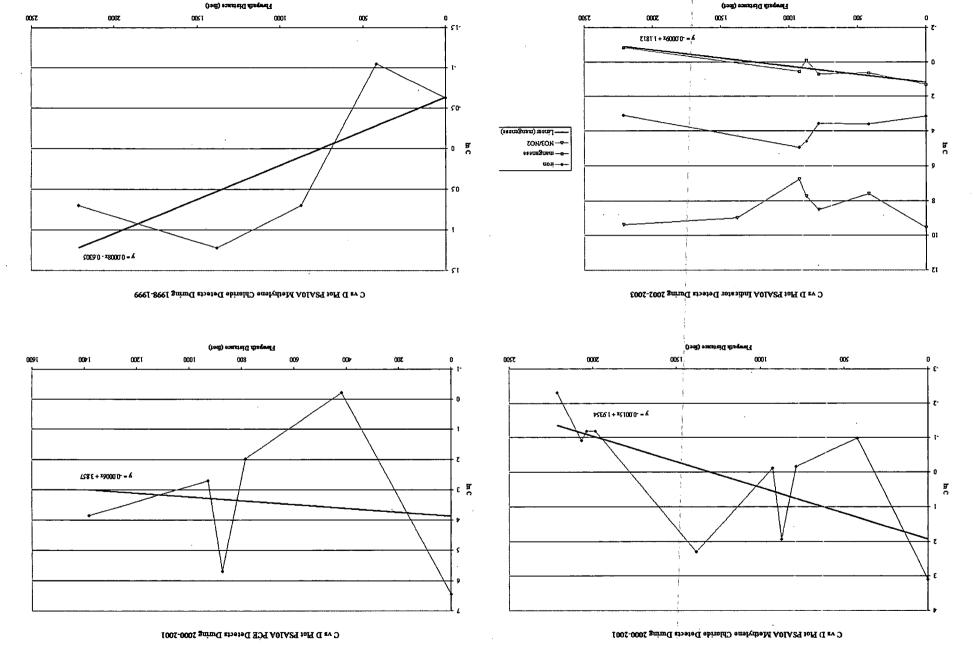
C vs D Hot PSA10A cis-1,2-DCE Detects During 2000-2001

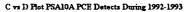
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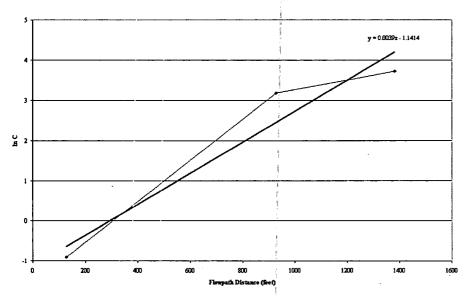
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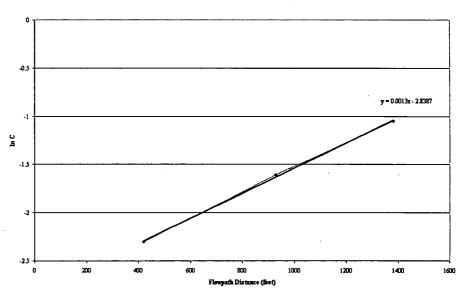






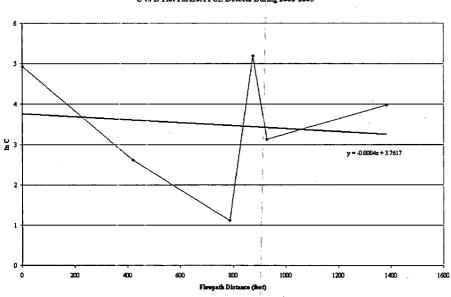
#### Detects During 1992-1993 C vs D Plot PSA10A 1,1,1-TCA Detects During 1998-1999

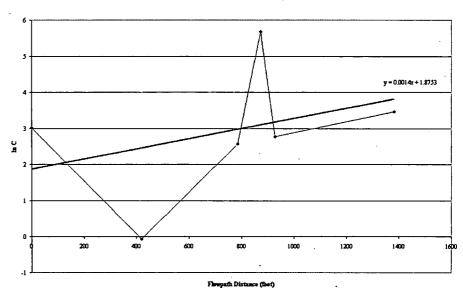




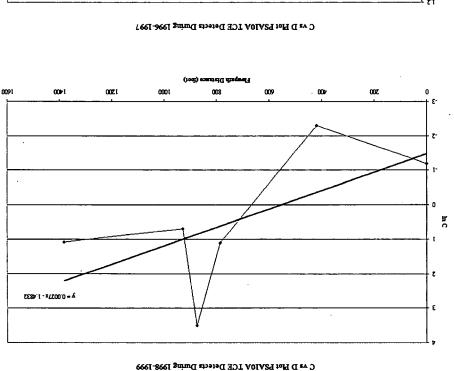
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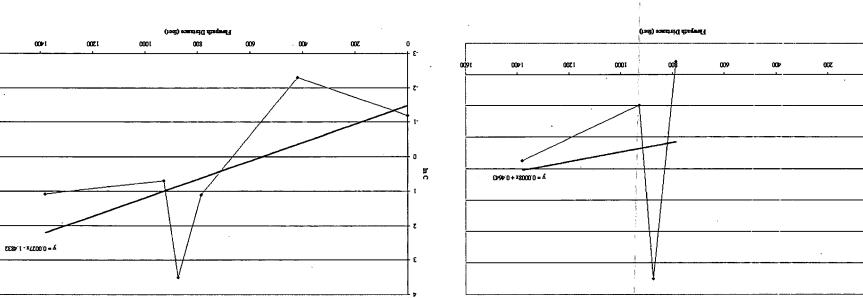
C vs D Flot PSA10A PCE Detects During 1998-1999

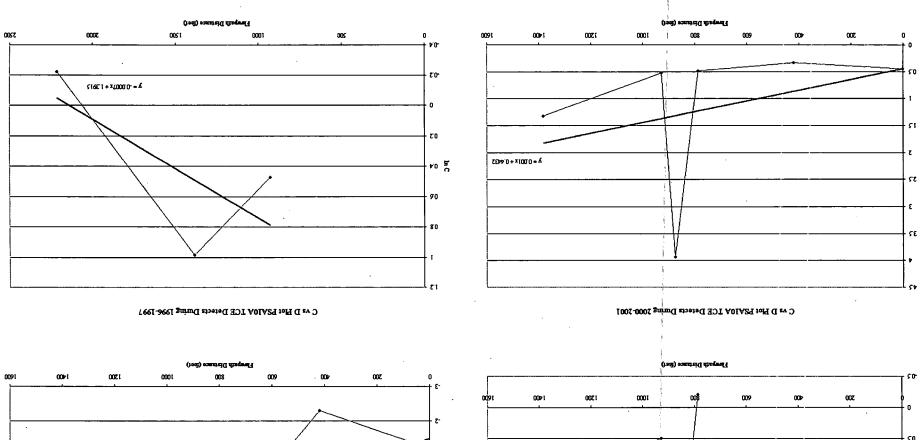


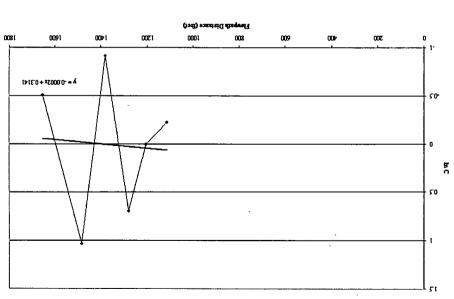


C vs D Part PSA10A TCE Detects During 2002-2003

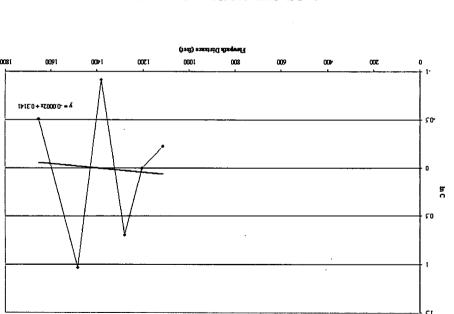


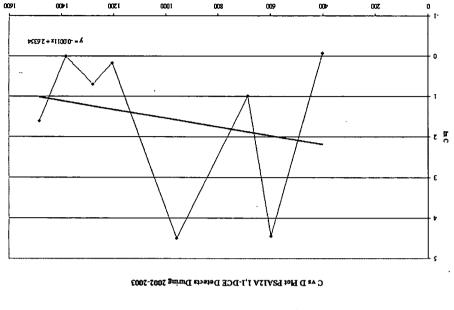




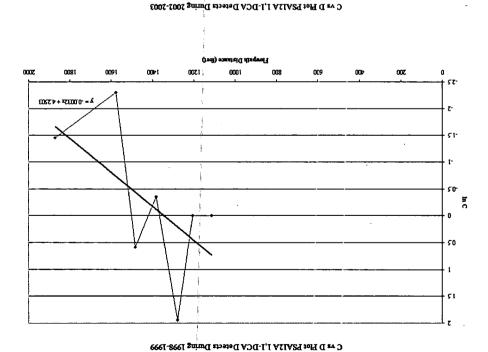


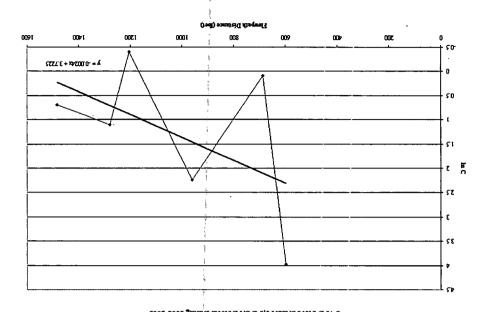
C vs D Flot PSALLA I, I-DCE Detects During 1998-1999

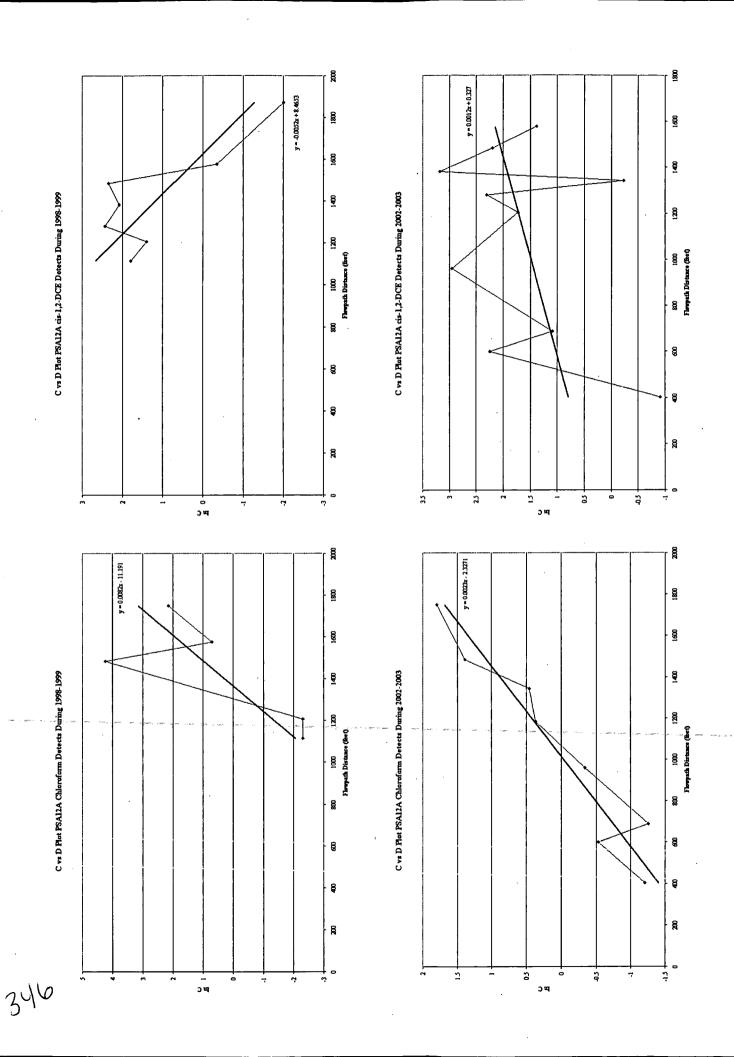




(bod) exacted disqual?







y = -0.0019x + 3.1611 8 9 y = -0.0001x + 2.6105 909 909 C vs D Flot PSA12A Methylene Chlaride Detects During 1998-1999 6 8 C vs D Flot PSA12A PCE Detects During 2002-2003 1 1000 12 Pawpath Distance (Sect) 1 1000 1 Flowparth Distance (feet) 8 엻 5 -25 2 5 Ü ρц рς y = -0.0002a - 0.7457 y = 0.0039x - 3.4191 0<u>8</u>1 1600 C vs D Hot PSA12A Carbon Tetrachloride Detects During 1998-1999 C vs D Flot PSA12A Methylene Chlaride Detects During 2002-2003 8 8 138 0 1000 12 Flowpath Distance (Sect) 600 800 Flowpath Distance (Sect) 8 8 8 4.0

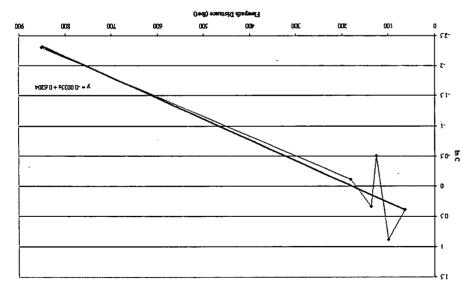
y = 0.0001x + 2.103180 999 909 8 8 C vs D Hot PSA12A 1,1,1-TCA Detects During 1998-1999 C vs D Flot PSA12A TCE Detects During 2002-2003 8 O 1000 1. Flowpach Distance (Sect) 800 1000 Plempath Distance (Sect) 8 A line will not be fitted to this non-linear dateset. 8 8 8 90 р С -12 07 <u>6</u> 8 1400 y = -0.0017x + 3.0185 82 1200 1600 8 140 C vs D Hot PSA12A 1,1,1-TCA Detects During 2002-2003 C vs D Hot PSA12A PCE Detects During 1998-1999 1000 1200 Powpath Distance (Sect) 600 800 Newpath Distance (Rect) **§** ă 2 E э**ч** 5 5



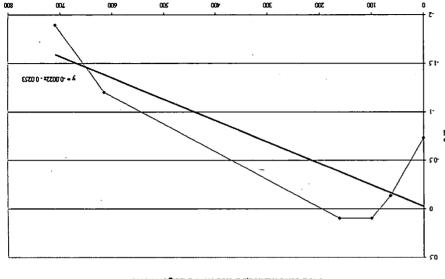


1420

652L'9+=700'0-= K

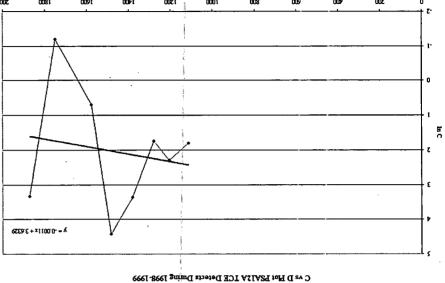


### C vs D Plot PSAL4A I, I-DCA Detects During 2000-2001



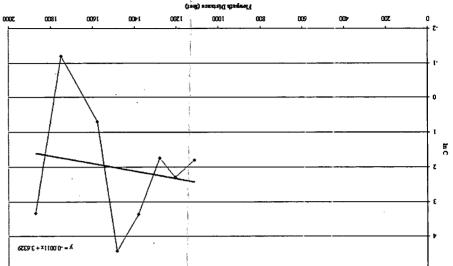
(bed) exacted disquess

# C vs D Plot PSALLA Vinyl Chloride Detects During 2002-2003

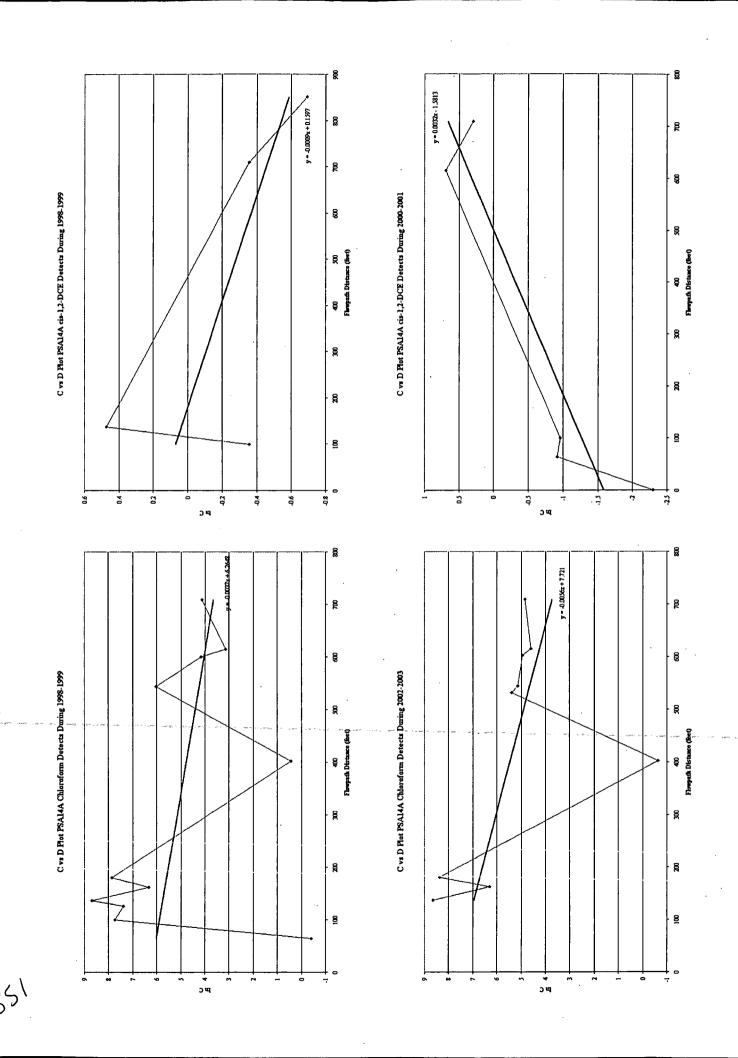


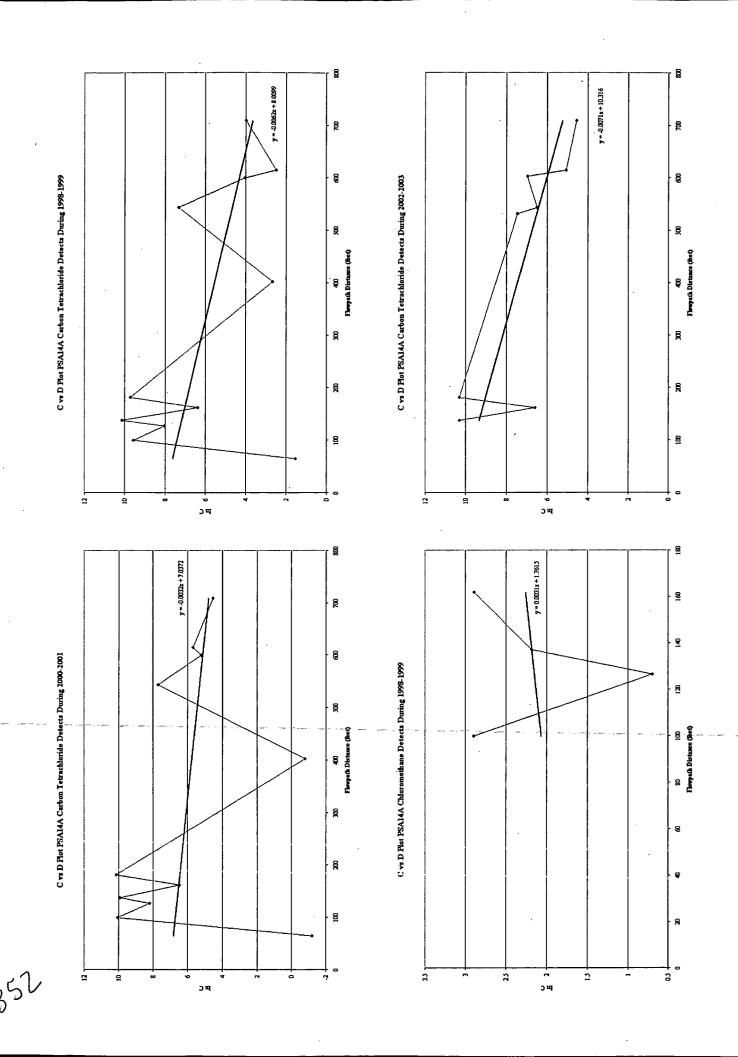
(heek) sounstried altequeeff

1300

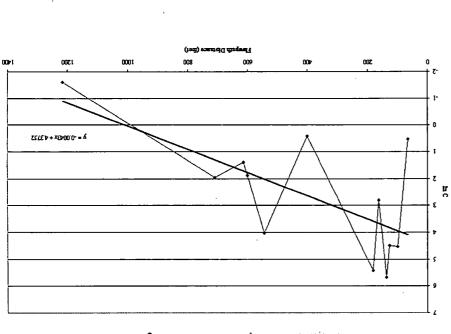


y = -0.0067x +8.222 y = -0.0029x +1.2225 8 C vs D Hat PSA14A Chloroform Detects During 2000-2001 C vs D Hot PSA14A 1,1-DCE Detects During 1998-1999 400 Flowpath Distance (Sect) 400 Flowpath Distance (Sect) 용 ğ g ä ਹ**ਯ** ສ 2 ģ 24 y = 0.0003x + 1.0148 y = 0.0016x + 0.4719 8 8 C vs D Flot PSA14A 1,1-DCE Detects During 2002-2003 C vs D Flot PSA14A 1,1-DCE Detects During 2000-2001 300 400 Florepath Distance (Sect) Ħ 뎚 12.7 2 5

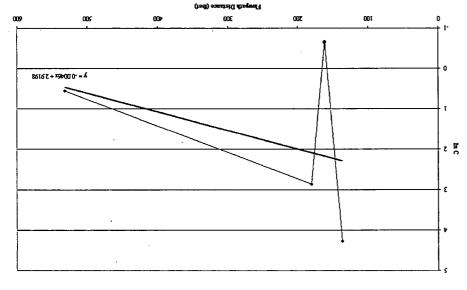




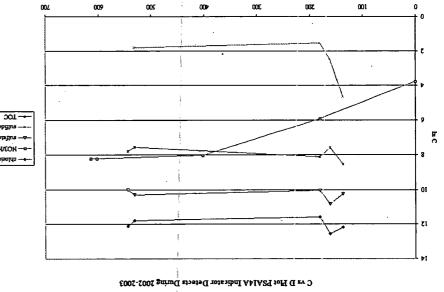
C vs D Flot PSAl4A Methylene Chloride Detects During 1998-1999



C vs D Flot PSAl 4A Methylene Chloride Detects During 2002-2003



C vs D Flot PSAl4A Methylene Chloride Detects During 2000-2001

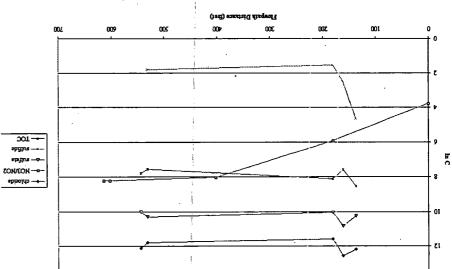


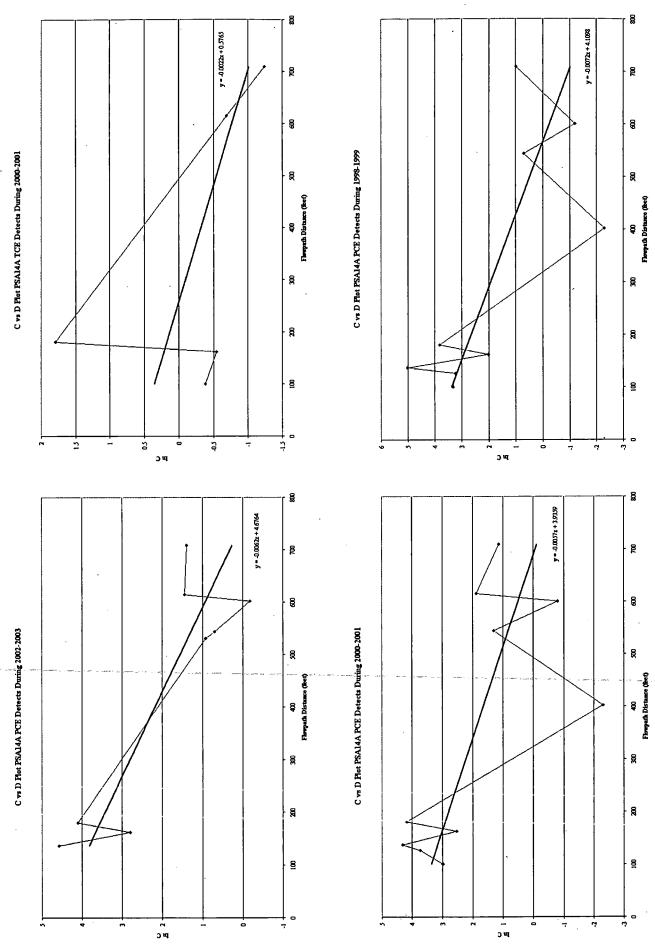
(hed) exesteid shaqeed?

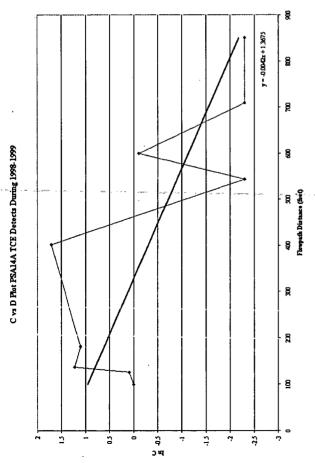
300

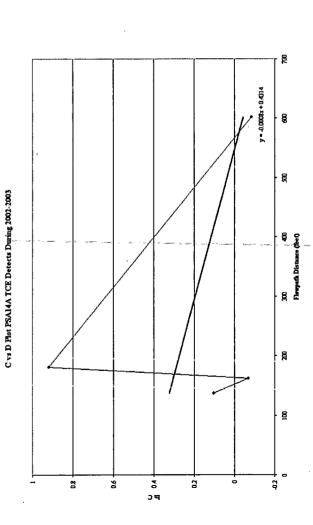
000

1698 E + 3/200 0 - 4









#### APPENDIX D

# BULK ATTENUATION AND BIODEGRADATION RATE CONSTANT CALCULATIONS AND SUPPORTING DATA

EETZZ.0			worg 071	122	n i	2.49	þ.I	69905.0	1.992	£.438	170.01	0.0	2.801	16070	01°Z	1.0	170.0	OZ I	06100'0-	cis-1,2-DCE	1661-7661	V	
\$8\$70.0			1290 grow						£.£81	£.433	1290.021		0.012	16020					0+000.0-		\$661-1661		
£7222.0			wong 00.E1						L'06	£.+66	1300.02		0.0343	16070				ς	02200.0-		\$661-1661		L
	6.0	91557.0	1050 steady	SZOI					£.172	£ 199	0.0201		2.82	16070					0+200.0-		\$661-1661		
<b>5977E.0</b>			VOTS EST	1567	61	4.32	0.5	94825.0	8.621	£.433	0.0251	8.928	3300.0	24663	2.10	1.0	851.0	5	02200.0-	CI.	1664-1662	V	L
06664,0			150 grow	300€	I	2.49	5.1	95524.0	L'99Z	£.433	0.021	0.0	9.911	16070	2.10	1.0	170.0	04	07100.0-	cis-1,2-DCE	\$661-1661	V	IZ
££909.0			worg 8	984	ı	2.03	1.2	88988.0	\$.T.£	£.433	0.252	8.928	0.012	24993	5.10	1.0	61-0.0	100	07100.0-	CŁ	\$661-1661	V	L
67352.0			worg El	2005	6	2.95	1.6	0.22496	0.225.0	£.433	540.0	8.928	0.58	24993	2.10	1.0	£60.0	L	-0.00100	1),1-DCE	\$661-1661	V	L
	6'0	04897.0	Vbsətz 0			<b>PS.</b> 9	7.1	77882.0	S.101	€.438	\$ 8.628	8.628	123.5	24993	0.1 2.10 24993			500	08200.0-	1,1,1,TCA			
07424.0			worg 16£	8271	II	4.32	LI	0.40000	8.621	£.433	1150.02	0.687	£.£8Þ	1 2.10 11891		1'0	881.0	ç	09700'0-	LI LI	L661-9661	V	L
		0.21205	0 steady	0					225.0	£.433	£ 2.442	2.442	77		16121 01.2		1		06000.0-		L661-9661		
		E60E0.0	0 steady						2.101	£.433	£ 2.442	2.442	14.4	16171					0.00030	1,1,1,TCA			
	٤٦	8£812.0	1500 steady					41824.0		£.438	0.0021	0.0	0.821	16070			221.0		0.00250		2002-2003		
29552.0			worg 0221						7.06	£.433	0.0221		0.0798	16070					0.00230		2002-2003		
		09294.0	0 steady						L'99Z	£.433	€ 0.0	0.0	6.43	16070					09100.0-	cis-1,2-DCE			
	9'1	0.44326	O steady						0.225	€.1-33	£ 2.442	2.442	2.2	15151			1000		08100.0-		£002-2002		
76615.0			wong 7911						6.261	0.017	0.0031		6142.0	<b>\$</b> 10			0.125		02100.0-		L861-9861		
p1620.0			wo18 7911						6.682	0.017	0.0081		0.0902	1/10					0.00010		1661-0661		
	1.0	02£07.2	147 steady	10.11					6.94€	0.017	0.022	8.201	350.0	1 1/10			1		05010.0-		1992-1993		
1.01430	C:0	*****	worg 222						0.76	0.017	100001		11470.0	L6800			1 2 2 2	5	02000.0-		6661-8661		
	5.0	17154.5	ybsəsi 229						6.682	0.017	1400.0		0.7802	L6800			690'0	<u>}</u>	0.00500.0-		6661-8661		5
98886'7			575 grow 875 shrink	1					6.261	0.017	0.0251		0.0001	£6800			\$21.0	<u>&gt;</u>	00010'0-		1002-0002		
£9996'1			worg 27.5			+			0.76	0.017	2 0.0001		0.00081	L6800			105.0		0.010.0-		2000-2001 2000-2001		
60727'7			375 grow		1-				6.682	0.017	0.028	8.474	0.0141	L6800					00010.0				
\$270.\$ \$726.0			worg 224					7,72519 7,72519	6'\$61	0.017	0.078	8.474	1120.0	L6800			20.0	2	014600.0-		2002-2003		
2.24988			15 shrink						285.0	0.017	0.064		2.17	£6800			1	0/	00900.0-	cis-1,2-DCE			
	<b>p</b> .0	1.84501	O steady		-				6.645	0.017	£ 8.474	8.474	6.2	L6800					0.00430		2002-2003		
<b>19559.0</b>	V U	10578 1	worg 76						32.0	2.46	0.077	2.673	1,361	16840					0.01240		1992-1993		
90ETA.0			dainda 77				1		14.4	5.46	0.027	2.573	1.884	16820					02710.0-	A3T-1,1,1			
\$0856.0			Juinds 770						3.85	5.46	0.0251		0.1842	16570					000+10.0-		2000-2001		
	7.0	25066.0	VDB318 764				1.4		1.62	5'76	0.0711		0.2265	16570			<del></del>		00610.0-		2002-2003		ε
7£600.0		CC000 0	WOTS \$821						6.21	5.46	0.0261		6.959	16990				S	07000.0-		£661-Z661		z
97210.0			1634 grow						3.85	5.46	0.0002		0.422£1	16990				ç	04000.0-		£661-7661		
0.03542			worg \$591						6.12	5.46	0.0002		2.01-085	16990					02100.0-		1992-1993		
£8820.0			WOTS						9.94	5.46	0.7731		0.25025	16990					09000.0-		1992-1993		Z
67120.0			worg \$52						32.0	5 76	0.009	1.99£	25.3	16990				L	02100.0-		1992-1993		z
	0.7	9£660.0	0 steady			22.2			9.24	5.46	\$ 1.395	1.99£	2.48	16990	2.10	1.0	820.0	3650	01200.0-	1'1-DCV	1992-1993	V	7
		75550.0	O steady						ול'ל	5.46	£ 1.99£	1.99£	8.£9	16990					05100.0-	ADT-1,1,1			
85510.0			worg 2821	\$606	646	€9.€	2.52	0.01303	1.92	5.46	2 0.0271	165.4	472.0	16151	2.10	1.0	521.0	s	02000.0-	TCE	1994-1995	ı v	z
7£600.0			worg 2701	E#9#	09€	ZE.T	L'9L	<b>†0600'0</b>	6.21	5.46	2,1 0.0071	8.429	129.0	16690	2.10	1.0	105.0	S	07000.0-	IACE	\$661-1661	V	Z
Z8981.0			wo18 922	6891	ÞÞ	2.45	2.4	25421.0	38.6	5.46	0.25.0	1.38£	4300.0	16990	2.10	10	690'0	S	00400.0-	MC	5661-9661	ı v	7
£2040.0			worg \$£\$!	0955	724	4.32	9.81	0,03720	6.12	5.46	2 0.0081	1.88£	0.73353	16990	2.10	1'0	821.0	s	07100.0-	13	5661-1661	V	Z
69490.0			WOTS ALS	6648	78	2.03	<b>11.4</b>	22090.0	9.94	5.46	0.009	1.88£	0.786£1	16990	01.2	1'0	610.0	001	-0.00130	CE	\$661-1661		7
£7831.0			worg č l	047	23	2.95	0.8	19751.0	32.0	5.46	0.081	165.4	₽.89I	16161	2.10		1000		-0.00430		\$661- <del>16</del> 61		Z
	74.4	24820.0	ybests 0						p p l	5.46	£ 4.281	165.4	6.E1	16161					08100.0-	1,1,1-TCA			
85510.0			worg \$£81	1911	SLZ	₹9.€	2.52	£0£10.0	1.92	5.46	1 0.0022	1.998	0.081	16990	2.10	1.0	221.0	ç	00000.0-	TCE	6661-8661		Z
	6.E1	66640.0	1734 steady		791	ZE.T			15.9	5.46	0.0012		0.0864	16990		1.0		S	0.00330		6661-8661		
60461.0			worg   [ £ i					97211.0		2.49	0.7781		0.01241	16990				S	000000-		6661-8661		
97480.0			worg 4581						21.9	5.46	0.0022		0.02254	16990				S	0.00330		6661-8661		7
08660.0			worg 484						9.94	2.46	0.028	1.99£	0.0275	16990				100	07000.0-		6661-8661		7
91050.0			Jainds 460			26.2			0.25	5.46	100001		0.2	16990			£60.0	L	06000.0-		6661-8661		7
	8.131	82400.0	Vbeste 0			2.22			9.24	5.46	E \$.201	p.29I	0.1	16151				3650	01000.0-		6661-8661		7
6240E.0			Aninda 522						9.8€	5.46	0.0061		8.6	16700			690'0	5	009000		2000-2001		7
16520.0			worg 2701		214				15.9	5.46	2 0.0071		0.242	16690				ç	-0.00170		2002-2003		7
7£840.0			2035 grow			4.32			6.12	5.46	0.0052		0.0966	16151				\$	0.00200		2002-2003		
97260.0			Janiak 200			2.49			6.TE	5.46	1290.011.3		9.62	16690				0L	06000.0-	cis-1,2-DCE			7
20640.0			worg 211			2.03			9.94	5.46	0.088	1.895	0.00201	16990				001	00100.0-		2002-2003		7
(21 82460.0		<u> </u>	wmg 27.1	609	61	2.95	€.8	0.08320	32.0	5.46	340.0	165.4	Penod 34.1	16161	016	1.0	£60.0	-	09200.0-	ET-DCE	£002-2003	·   V	Z
12)			Source (notes 5,6,7)	1 '	1 1	1		'	1		(บ	i) (ii)	1	1		1	1 '	1		1	i	1 '	
at steady		(11 ston		Source	Dote 4)		(£1	1			ba3 s		During N	Source	1	(+1	1	1	1	1	i	1 '	
(plume not	life (yr.)	per yr.,	Trom Well time period of with Max Column C	xeM diiw		1	310g (yt,	(per yr)	(17/11)	1 (160)	dient	TR 20 IDOC		Inferred	Кһо g/ml	(0, note	1 '	7/8n	(bet y)			1 '	
ton amula)	-life (vr.)	order lambda,			II raiT		Half-life	Rate K	velocity (fl/vr)	Velocity (fl/yr)	solon -aw	on   -	_	Near	Density	1	8/ш ру			Срешнові	Period	batp	ا ,ین ا
ation rate	-bargsboid -land noits	constant (1st	Plume grow or Length (ft) shrink after	Length (ft)		Я	noise	Auen.			-1004 II T	Well Near		Max Conc	和u	Effective		II TaiT		[enimed]	əmiT	Flow-	AS4
-bergsboid ster noite	-heroshoi8	Sist goils	Existing predicted to Plume grow or	Decay	time (yr)		-nueny	Bulk	202	Water	· Jo sou	Bisid Jo Samersid	Jo 7/8n I II>M	ts disq	USHU		'	II TOIT	DC vs D	1	i	'	
		-bangaboid		Predicted	decay	1	Britk	1 '	1	1 1	qn			Well # on		USHU	1 '	1	1	1	i	1	
		-heroshoisi	er animid an i hamisissa	pon;pond	1																		
Rough estimate of		hanshois	Estimated The plume is	poor;poor	"""		"				pated	Measured Estin	Max			1		1		1	1	1 1	ļ ļ



									,														, <u>.</u>		
							ì		1 1	Max		Estimated					1 1			1					Rough
									Well # on	Conc	Measured	Path	4				Bulk		decay	Predicted		The plume is	Biodegrad-		estimate of
				!	1		UHSU	UHSU	path at	ug/L of	Path	Distance of			'	Bulk	Attenu-		time (yr)	Decay	Existing	predicted to	ation rate		biodegrad-
	l			InC vs D	Tier II	i	Effective			Well	Distance of			Water	coc						Plume	grow or		Biodegrad-	ation rate
PSA	Flow-	Time	Chemical	Slope	C Goal	Kd ml/g	Porosity	Bulk	Max Conc	Near	Well Near		Foot-	Velocity	velocity	Atten.	ation	R	to meet	Length (ft)	Length (ft)	shrink after	constant (1st	ation half-	constant
	path	Period		(per ft)	ug/L		(n, note	Density	Near	Source	Source at	Down-	notes	(fl/yr)	(fl/yr)	Rate K	Half-life		Tier II	from Well		time period of	order lambda,	life (yr.)	(plume not
ŧ l				(Jac. 11.)	ug/L		14)	Rho g/mi	Inferred	During	Max Conc.	gradient	1	(,	(,.)	(per yr)	(yr, note		goal (see	with Max	with Max	Column C	per yr.,	(3,	at steady
f					1		14)		Source		,	Plume End					13)		note 4)	Source	Source		note (1)		
1 [					ŀ		1		1	Time	(ft)	(ft)					1			i	Source	(notes 5,6,7)	'		state, note
						1		<u> </u>	<b> </b>	Period		. ` `													12)
	A	1992-1993		-0.00110		0.301	0.1		02091	4608.0	0.0			664.3	90.7		6.9	7.32			1200				0.10559
	A	1992-1993		-0.00130		0	0.1		02091	200.3	0.0			664.3	183.3	0.23823	2.9	3.63							0.25452
7	A	1990-1991	1,1,1-TCA	-0.00290	200	0.264	0.1	2.10	2487	40.0	360.2	360.2	3	664.3	101.5	0.29439	2.4	6.54	-5	0	0	steady	0.33929	2.0	l
7	Α	1990-1991	1.1-DCE	-0.00540	7	0.093	9 0.1	2.10	2487	31.0	360.2	640.0		664.3	225.0	1.21477	0.6	2.95	1	· 276	280	steady	1.55982	0.4	ĺ
7	Α	1990-1991	cis-1,2-DCE	-0.00150	70	0.071	0.1	2.10	02091	47.0	0.0	0.0	3	664.3	266.7	0.40002	1.7	2.49	-1	Ö		steady	0.43158	1.6	
7	A	1990-1991		-0.00090	5	0.158	0.1	2.10	0374	444.0	682.7	900.0	2	664.3	153.8	0.13846	5.0	4.32	32	4985	217	grow			0.14501
	A	1990-1991		-0.00080	5	0.069	0.1		2587	7.0				664.3	271.3	0.21700		2.45				steady	0.22613	3.1	
	Α	1990-1991		-0.00060			0.1		2587	305.6				664.3	90.7	0.05444		7.32				grow			0.05616
				-0.00030			0.1		02091	94.0				664.3	183.3	0.05498		3.63				grow			0.05584
		1990-1991																					0.02422		0.05384
10			cis-1,2-DCE	-0.00110			0.1		41299	23.4				54.2	21.8	0.02393		2.49				steady	0.02532	27.4	
10		2002-2003		-0.00040		0.301	0.1		41299	179.0			<u> </u>	54.2	7.4	0.00296		7.32				grow			0.00302
10		2000-2001		-0.00150	<del></del>	0.069	0.1		10498	22.3				54.2	22.1	0.03320	20.9	2.45				steady	0.03582	19.4	
10		2000-2001		-0.00060	5		0.1		10498	627.4				54.2	7.4			7.32			1450				0.00458
10		1996-1997	TCE	-0.00070		1 0	0.1		P416889	2.7				54.2	15.0		66.2	3.63				steady	0.01085	63.9	
12	A	2002-2003	1,1-DCA	-0.00240	3650	0.058	0.1	2.10	84702	53.4	597.6	597.6	3	502.0	226.3	0.54319	1.3	2.22	-8	0	0	steady	0.61176	1.1	
12		2002-2003		-0.00110		0.093	0.1		84702	85.2	597.6	1150.0		502.0	170.0	0.18700	3.7	2.95		2272		grow			0.19782
12		2002-2003		-0.00020			0.1		84702	0.7			3	502.0	205,0			2.45				steady	0.04143	16.7	
12		2002-2003		-0.00010			0.1		84702	309.7		1670.0		502.0	68.6			7.32							0.00689
12			vinyl chloride	-0.00400			0.1		21798	9.0		1550.0		502.0	495.8	1.98301		1.01		<del></del>		grow			2.40024
12		1998-1999		-0.00320			0.1		21798	7.0		1279.1	,	502.0	226.3	0.72426	1.0	2.22			2/1	steady	0.84616	0.8	
					3030									502.0				2.95					0.84010	U.8	0.03436
12		1998-1999		-0.00020		0.075	0.1		21798	2.0					170.0										
12			cis-1,2-DCE	-0.00520			0.1		21798	11.3			3	502.0	201.5	1.04793		2.49				steady	1.33456	0.5	
12		1998-1999		-0.00190			0.1		21598	21.1				502.0	205.0	0.38947		2.45				grow			0.42839
12		1998-1999		-0.00170			0.1		21598	11.6				502.0	68.6	0.11657		7.32				grow			0.12699
12	A	1998-1999	TCE	-0.00110	5	0.125	0.1	2.10	21598	83.4	1483.5	1900.0	2	502.0	138.5	0.15233	4.5	3.63	18	2558	417	grow			0.16114
14	A	2002-2003	CF	-0.00560	100	0.049	0.1	2.10	18499	5665.0	136.9	610.0		88.0	43.4	0.24288	2.9	2.03	17	721	473	grow			0.31442
14	A	2002-2003	СТ	-0.00710	5	0.158	0.1	2.10	18199	29700.0	180.7	800.0	2	88.0	20.4	0.14470	4.8	4.32	60	1224		grow			0.19874
14	A	2002-2003	MC	-0.00460	5	0.069	0.1	2.10	18499	71.2	136.9	400.0		88.0	35.9	0.16529	4.2	2.45	16	577		grow			0.20529
14		2002-2003		-0.00620			0.1		18499	96.0		510.0		88.0	12.0			7.32	40	477	373	grow			0.09883
14		2002-2003		-0.00080		0.125			18199	2.5			3	88.0	24.3			3.63				steady	0.02024	34.2	
14		2000-2001		-0.00220			0.1		18599	1.1				88.0	39.7			2.22				steady	0.02024	7.1	
				-0.00220						4696.0				88.0	43.4			2.03					0.39299	1.8	
14		2000-2001					0.1		18499								+					steady	0.39299	1.8	
14		2000-2001		-0.00320		0	, 0.1		18199	25423.0			2	88.0	20.4			4.32				grow			. 0.07619
14		2000-2001		-0.00240			0.1		18599	2038.0				88.0	35.9	0.08624		2.45			530	grow			0.09713
14		2000-2001		-0.00570			0.1		18499	74.7				88.0	12.0			7.32				steady	0.08906	7.8	
14		2000-2001		-0.00220		0.125			18199	6.0				88.0	24.3	0.05341		3.63				steady	0.05959	11.6	<del> </del>
14	Α	1998-1999	1,1-DCA	-0.00350	3650	0.058	. 0.1	2.10	18599	2.4		99.7	3	88.0	39.7	0.13886		2.22		0	0	steady	0.16443	4.2	
14	A	1998-1999	1,1-DCE	-0.00290	7	0.093	0.1	2.10	18799	7.0	161.7	161.7	3	88.0	29.8	0.08642	8.0	2.95	0	0	0	steady	0.09960	7.0	
14	Α	1998-1999	CF	-0.00370	100	0.049	0.1	2.10	18199	2608.0	180.7	580.0		88.0	43.4	0.16047	4.3	2.03	20	881	399	grow	1		0.19170
14	A	1998-1999	cis-1,2-DCE	-0.00090	70	0.071	0.1	2.10	18499	1.6	136.9	136.9	3	88.0	35.3	0.03179	21.8	2.49	-119	0		steady	0.03330	20.8	
14		1998-1999		-0.00620			0.1		18599	14073.0				88.0	20.4			4.32				grow			0.16756
14	<del></del>	1998-1999		-0.00430		<del></del>	0.1		18499	287.8				88.0	35.9			2.45				grow			0.18946
14		1998-1999		-0.00720		0.301	0.1		18499	150.0				88.0	12.0			7.32				grow	<del></del>		0.11932
14	•••	1998-1999		-0.00720		0.125	0.1		22696	5.5				88.0	24.3			3.63			233	grow			0.11932
14	<u>  ^                                   </u>	11770-1779	1106	-0.00420	<del> </del>	0.123	1 0.1	4.10	122070	3.3	401.0	410.0		88.0	24.3	0.10190	0.8	3.03	<del>                                     </del>			B <sub>1</sub> OW			0.12448
			<del></del>	<b></b>			1	ļ			<b>!</b>	ļ		ļ	ļ	ļ	ļ		<b> </b>				l		<del> </del>
L	L	<u> </u>		<u> </u>	<b></b>	<del> </del>	ļ	1	-	L	ļ	<b> </b>			l		ļ ļ			<u> </u>					
Footno		L	L	<u> </u>	1	ـــبــــــــــــــــــــــــــــــــــ	Ц.,.				<b> </b>	<del> </del>		ļ		<u> </u>			<del> </del>						<u> </u>
1 - The	ta Dulated	maximum con	centration represents the upgr	agient source at	rea, a mgbe	er maximum	is round dow	ngradient.	Links 1	l "	<del> </del>	<del>  </del>			<u> </u>	<del></del>						<u> </u>			<u> </u>
			dient plume end at Tier II is e centration near the source is a								noth is the	<del>. </del>			<del></del>	<del> </del>	<del>  -  </del>		<del> </del>			L	<b>-</b>		
			es indicate that the max conce								warm to men seat	1			<b>-</b>	<del></del>	1		<del> </del>	<del>                                     </del>					<del></del>
			w when the predicted decay I								<u> </u>	1		-	<del> </del>		1			<u> </u>					
			ink when the predicted decay								<del>                                     </del>	<del> </del>		<del>                                     </del>			1 1	-	<u> </u>	1					
			steady state when the predicte									1		<b></b>	<b>i</b>	<u> </u>	1		<del> </del>	l — —					
			taken as 53 feet, which is the					Ť		i	T					l — —			I	· · · · · ·					<del>                                     </del>
		e plume length		T	52.6																				
			re not used because some plus	mes were define	ed as havin	g zero Tier	I plume leng	th, preventin	g calc of lambd	٠									L						L
			stion requires steady state plu																						
12 - Ro	ugh estim	ate of ismbda	ecause the plume is not predi	icted to be at ste	ady state (	or the chemi		period.																	
			acribes the chemical's persist														$\perp$								
14 - RF	CA Annu	al Groundwate	r Monitoring Reports have us	ed effective por	rosity as 0.	1.	I i		1		l				l	i	<u> </u>		1	1					

Cale attenuation rate constants 10-26-03.xls

11.998	14510	16990	1.2	1.0	690.0	ς	£00.0-	MC	1668-1666	V	7	15
966.14	43220	16990	1.2	1.0	821.0	S	££00.0-	CT	1668-1666	¥	7	П
\$1.995	0572	16990	1.2	1.0	640.0	100	7000.0-	CF	1998-1999	¥	7	10
41.998	·	16990	1.2	1.0	660.0	L	6000.0-	1'1-DCE	1998-1999	¥	7	6
165.35	I	16181	1.2	1.0	820.0	3650	1000.0-	I'I-DCA	6661-8661	¥	7	8
91.7781	8.6		1.2	1.0		S	900.0-	MC	2000-2001	¥	7	L
8.428	545			1.0			7100.0-	<b>b</b> CE	2002-2003	¥	7	9
165.4	0966		1.2	1.0		ς	200.0-	CT	2002-2003	¥	7	ς
8.428	9.68			1.0		02		cis-Ĭ,2-DCE	2002-2003	∀	7	Þ
1.99£	10501			1.0	670.0	100	100.0-	CE	2002-2003	<u> </u>	7	ε
25.231	1.45	19191	1.2	1.0	660.0	L	9700.0-	I'I-DCE	2002-2003	¥	7	7
Measured Path Distance of Well Near Source at Max Conc. (ft)	Max Conc ug/L of Well Mesr Source During Time Period	Well # on path at Max Conc Mear Inferred Source	UHSU Bulk Density Rho g/ml	UHSU Effective Porosity (n, note 14)	Kd ml/g	Tier II C Goal ug/L	InC vs D Slope (per ft)	Chemical	Time Period	Flow-	A≳¶	
Γ	K	ı	I	Н	Ð	4	E	D	ວ	В	A	

	M	N	Го	P	Q	R	S	T
1	Estimated Path Distance of Tier II Down- gradient Plume End (ft)	Foot- notes	Water Velocity (ft/yr)		Bulk Atten. Rate K (per yr)	Bulk Attenu- ation Half-life (yr, note 13)	R	decay time (yr) to meet Tier II goal (see note 4)
2	340		94.5	=O2/S2	=E2*(-1)*P2	=0.6931/Q2	=G2*I2/H2+1	=(-1)*LN(F2/K2)/Q2
3	880		94.5	=O3/S3	=E3*(-1)*P3	=0.6931/Q3	=G3*I3/H3+1	=(-1)*LN(F3/K3)/Q3
4	1290	1,3	94.5	=O4/S4	=E4*(-1)*P4	=0.6931/Q4	=G4*I4/H4+1	=(-1)*LN(F4/K4)/Q4
5	2200		94.5	=O5/S5	=E5*(-1)*P5	=0.6931/Q5	=G5*I5/H5+1	=(-1)*LN(F5/K5)/Q5
6	1700	2	94.5	=O6/S6	=E6*(-1)*P6	=0.6931/Q6	=G6*I6/H6+1	=(-1)*LN(F6/K6)/Q6
7	1900		94.5	=O7/S7	=E7*(-1)*P7	=0.6931/Q7	=G7*I7/H7+1	=(-1)*LN(F7/K7)/Q7
8	165.35	3	94.5	=O8/S8	=E8*(-1)*P8	=0.6931/Q8	=G8*I8/H8+1	=(-1)*LN(F8/K8)/Q8
9	1000	1,3	94.5	=O9/S9	=E9*(-1)*P9	=0.6931/Q9	=G9*I9/H9+1	=(-1)*LN(F9/K9)/Q9
10	850		94.5	=O10/S10	=E10*(-1)*P10	=0.6931/Q10	=G10*I10/H10+1	=(-1)*LN(F10/K10)/Q10
11	2200		94.5	=O11/S11	=E11*(-1)*P11	=0.6931/Q11	=G11*I11/H11+1	=(-1)*LN(F11/K11)/Q11
12	1677		94.5	=O12/S12	=E12*(-1)*P12	=0.6931/Q12	=G12*I12/H12+1	=(-1)*LN(F12/K12)/Q12

	U (		V	W
1	Predicted Decay Length Well with Max Sou		Estimated Existing Plume Length (ft) from Well with Max Source	The plume is predicted to grow or shrink after time period of Column C (notes 5,6,7)
2	=IF(P2*T2<=0,0,P2*T2)	ı	=M2-L2	=IF(U2-1.25*V2>0,"grow",IF(U2-0.75*V2<0,"shrink","steady"))
3	=IF(P3*T3<=0,0,P3*T3)		=M3-L3	=IF(U3-1.25*V3>0,"grow",IF(U3-0.75*V3<0,"shrink","steady"))
4	=IF(P4*T4<=0,0,P4*T4)		=M4-L4	=IF(U4-1.25*V4>0,"grow",IF(U4-0.75*V4<0,"shrink","steady"))
5	=IF(P5*T5<=0,0,P5*T5)		=M5-L5	=IF(U5-1.25*V5>0,"grow",IF(U5-0.75*V5<0,"shrink","steady"))
6	=IF(P6*T6<=0,0,P6*T6)		=M6-L6	=IF(U6-1.25*V6>0,"grow",IF(U6-0.75*V6<0,"shrink","steady"))
7	=IF(P7*T7<=0,0,P7*T7)		=M7-L7	=IF(U7-1.25*V7>0,"grow",IF(U7-0.75*V7<0,"shrink","steady"))
8	=:IF(P8*T8<=0,0,P8*T8)		=M8-L8	=IF(U8-1.25*V8>0,"grow",IF(U8-0.75*V8<0,"shrink","steady"))
.9	=IF(P9*T9<=0,0,P9*T9)	1	=M9-L9	=IF(U9-1.25*V9>0,"grow",IF(U9-0.75*V9<0,"shrink","steady"))
10	=IF(P10*T10<=0,0,P10*	T10)	=M10-L10	=IF(U10-1.25*V10>0,"grow",IF(U10-0.75*V10<0,"shrink","steady"))
11	=IF(P11*T11<=0,0,P11*	T11)	=M11-L11	=IF(U11-1.25*V11>0,"grow",IF(U11-0.75*V11<0,"shrink","steady"))
12	=IF(P12*T12<=0,0,P12*	T12)	=M12-L12	=IF(U12-1.25*V12>0,"grow",IF(U12-0.75*V12<0,"shrink","steady"))

	. X	Y	Z	AA
	Biodegradation rate constant (1st order lambda, per yr., note 11)	Biodegradation half-life (yr.)	Rough estimate of biodegradation rate constant (plume not at steady state, note 12)	longitud- inal disper- sivity (ft)
	=IF(W2="steady",AD2*AC2,"")	=IF(W2="steady",0.6931/X2,"")	=IF(W2<>"steady",AD2*AC2,"")	52.6
3	=IF(W3="steady",AD3*AC3,"")	=IF(W3="steady",0.6931/X3,"")	=IF(W3<>"steady",AD3*AC3,"")	52.6
4	=IF(W4="steady",AD4*AC4,"")	=IF(W4="steady",0.6931/X4,"")	=IF(W4<>"steady",AD4*AC4,"")	52.6
5	=IF(W5="steady",AD5*AC5,"")	=IF(W5="steady",0.6931/X5,"")	=IF(W5<>"steady",AD5*AC5,"")	52.6
6	=IF(W6="steady",AD6*AC6,"")	=IF(W6="steady",0.6931/X6,"")	=IF(W6<>"steady",AD6*AC6,"")	52.6
7	=IF(W7="steady",AD7*AC7,"")	=IF(W7="steady",0.6931/X7,"")	=IF(W7 $\diamond$ "steady",AD7*AC7,"")	52.6
8	=IF(W8="steady",AD8*AC8,"")	=IF(W8="steady",0.6931/X8,"")	=IF(W8<>"steady",AD8*AC8,"")	52.6
9	=IF(W9="steady",AD9*AC9,"")	=IF(W9="steady",0.6931/X9,"")	=IF(W9 $\Leftrightarrow$ "steady",AD9*AC9,"")	52.6
10	=IF(W10="steady",AD10*AC10,"")	=IF(W10="steady",0.6931/X10,"")	=IF(W10<>"steady",AD10*AC10,"")	52.6
11	=IF(W11="steady",AD11*AC11,"")	=IF(W11="steady",0.6931/X11,"")	=IF(W11<>"steady",AD11*AC11,"")	52.6
$\overline{}$	=IF(W12="steady",AD12*AC12,"")	=IF(W12="steady",0.6931/X12,"")	=IF(W12<>"steady",AD12*AC12,"")	52.6

	AB	AC	AD
1	inner part of 2nd term	second term	first term
2	=1-(2*AA2*E2)	=(AB2*AB2)-1	=P2/(4*AA2)
3	=1-(2*AA3*E3)	=(AB3*AB3)-1	=P3/(4*AA3)
4	=1-(2*AA4*E4)	=(AB4*AB4)-1	=P4/(4*AA4)
5	=1-(2*AA5*E5)	=(AB5*AB5)-1	=P5/(4*AA5)
6	=1-(2*AA6*E6)	=(AB6*AB6)-1	=P6/(4*AA6)
7	=1-(2*AA7*E7)	=(AB7*AB7)-1	=P7/(4*AA7)
8	=1-(2*AA8*E8)	=(AB8*AB8)-1	=P8/(4*AA8)
9	=1-(2*AA9*E9)	=(AB9*AB9)-1	=P9/(4*AA9)
10	=1-(2*AA10*E10)	=(AB10*AB10)-1	=P10/(4*AA10)
11	=1-(2*AA11*E11)	=(AB11*AB11)-1	=P11/(4*AA11)
12	=1-(2*AA12*E12)	=(AB12*AB12)-1	=P12/(4*AA12)

					8-6 aldsT (29	Bulk density 2.10 g/ml from EG&G(19
				.5	most conservative	Min Kd has the least retardation and is
				e B.2.1	EPA (1998) Tabl	All Koc values from the compilation in
6-8 of EG&G (1995) Geologic Char. Rpt.	epth from Table	b ft 04 ot 0 ft	mples fron	qozen ası	I to agerave ei 4	Alternative UHSU fraction OC= 0.0022
to 40 ft. depth.	23 boreholes at 2	I TOT TOT 10	records f	MS 442	mon seess from	UHSU fraction OC= 0.00144 computed
					1	NOLES
					14	
	44100.0	7	9000.0	4.0	ΛC	vinyl chloride
	44100.0	S	0.125	0.78	LCE	trichloroethene
	44100.0	04	220.0	0.38	trans-1,2-DCE	trans-1,2-dichloroethene
, .	44100.0	S	105.0	0.602	<b>b</b> CE	tetrachloroethene
	44100.0	S	690.0	0.84	MC	methylene chloride
	44100.0	0L	170.0	0.64	cis-1,2-DCE	cis-1,2-dichloroethene
assumed equal to chloroethane	pp100.0	<b>cc.</b> 9	840.0	0.88	СМ	сріототетрале
	44100.0	100	640.0	34.0	CE	chloroform
	pp100.0	4.62	840.0	0.88	CE	chloroethane
	44100.0	ς	821.0	110.0	CT	carbon tetrachloride
	44100.0	ς	840.0	0.88	I T-DCV	1,2-dichloroethane
	44100.0	L	£60.0	9.49	I'I-DCE	1,1-dichloroethene
	44100.0	3650	820.0	0.04	I'I-DCV	1,1-dichloroethane
	44100.0	ς	101.0	0.07	I,I,2-TCA	1,1,2-trichloroethane
	44100.0	200	492.0	0.£81	I,I,I-TCA	1,1,1-trichloroethane
References & Notes	noitaerit ainegro nodrea	II 19iT qu-nasələ J\gu laog	Min Kd ml/g	Min Koc mVg		Chemical



PSA	Area	start well	end well	Water Velocity ft/yr	Notes
2	903 Pad	06991	90099	94.5	from Fig. 3-1, draft 2002 RFCA Annual GW Mon. Rpt.
3	Ryan's Pit	06991	90099	. 94.5	-
5	Mound	00897	02291	710	was 356 using old start well 1987, changed 10/21/03
7	East Trenches	12191	95899	664.3	was 78.6, changed by J. Rosen 10/21/03 to 664.3
10	B444	40499	P416889	54.2	
12	B551	P114789	1986	502	
14	IHSS 118.1	00100	70799	88	S to N line through B771 (Section 5 of Rpt.)

1 11 0	S	S.	0	اري ا	m	9	_	_	_	-	_	_	7	_	_	-	_	_	7	-1	_	7	_	$\neg$
longitud- inal disper sivity (ft)	7.	7	15.0	7.5		52.6																		
Biodegrad longitud- ation half inal disper life (yr.) sivity (ft)	234.1	468.3	175.9	117.1	171.6						1	1												
Rough estimate of biodegradation rate constant (plume not at steady state, note 12)						0.09458								-		_								
Biodegrad- ation rate constant (1st order lambda, per yr., note 11)	0.00296	0.00148	0.00394	0.00592	0.00404							-				_								
The plume is predicted to grow or shrink after time period of Column C (notes 5,6,7)	steady	steady	steady	steady	steady	row		_				_				-								
Estimated Existing Plume Length (ft) from Well t with Max Source	s	<u>.s</u>	s	s	s	175 grow														_				
Predicted Decay Length (ft) from Well with Max Source						609																		
decay time Predicted (yr) to Decay meet Tier Length (f) Il goal from Well goal with Max 4) Source						19											_		_					
ĸ	2.00	2.00	2.00	1.00	1.00	2.95									_									_
Bulk Attenu- ation Half-life (yr, note				2	9	0 8.3	_												_				ates match.	
Bulk Atten. Rate k (per yr)	0.00198	0.00099			0.00396	0.08320																	radation n	
COC velocity (fl/yr)	0:030	0.015		090'0	090'0	32.0	-																case biodes	
Water Velocity (fVyr)	90.0	0.03	90.0	90.0	90.0	94.5						then zero.											. The test	
Foot- notes												length is											per day	
Estimated Path Distance of Tier II Down- gradient Plume End (ft)						340.0					ell control).	ctual plume	lecay away.						da.				/day, lambda	
Measured Path Distance of Well Near Source at Max Conc. (ft)						165.4					- Path distance of the downgradient plume end at Tier II is estimated to be beyond the last detected concentration (and possibly beyond well control)	without further attenuation. The actual plume length is then zero	4 - Negative and zero decay times indicate that the max concentration has met or exceeded the Tier II goal in the past, and will continue to decay away						g calc of lam	<ol> <li>Biodegradation lambda equation requires steady state plume, and follows Buscheck &amp; Alcantar (1995).</li> </ol>			Dispensivity in meters, velocity m/day, lambda per day. The test case biodegradation rates match	
Max Conc ug/L of Well Near Source During Time	3660.0	3660.0	3660.0	3660.0	3660.0	34.1				gradient.	fissod brus)	urther atten	ist, and will		ı.	ų.			, preventing		riod.		ity in meter	
Tier II UHSU UHSU path at CGoal Kd mb/g Proresity Density Near (a) Rho g/ml inferred (b) Rho g/ml inferred (c) Source						13191				- The tabulated maximum concentration represents the upgradient source area, a higher maximum is found downgradient	oncentration	al, without fi	goal in the pa	me length.	<ul> <li>Plumes were predicted to shrink when the predicted decay length was less than 75% of the existing plume length</li> </ul>	7 - Plumes are assumed to be at steady state when the predicted decay length is +/- 25% of the existing plume length	led by 10.		dume length	.(566	12 - Rough estimate of lambda because the plume is not predicted to be at steady state for the chemical and time period			
UHSU Bulk Density Rhog/ml					_	1 2.10 1				aximum is	detected	e Tier II go.	the Tier II	xisting plu	he existing	the existing	ngths, divic	_	no Tier II p	Alcantar (1	he chemica	e area.	calculation	
UHSU Effective Porosity (n)		2.00		-	-	0.0	part s	-	1	a higher m	ond the las	equal to th	exceeded	5% of the	n 75% of	-/- 25% of	II phune le	-	s having z	uscheck &	state for t	A the sourc	dation rate	ty as 0.1.
Kd ml/g						0.093				ce area;	be bey	than or	IS THE LOT	eded 12	s less thz	ngth is +	the Tier	E	lefined a	llows B	at steady	it has lef	biodegra	e porosi
Tier II C Goal						-				lient sour	imated to	eady less	tration h	agth exec	angth wa	decay le	nean of	53.0 feet	es were	re, and fo	ed to be	nce after	o verify	1 effectiv
inC vs D Tier II Slope C Goal (per ft) ug/L	-0.06600	-0.06600	-0.06600		-0.06600	-0.00260				s the upgrac	Tier II is est	3 - The tabulated maximum concentration near the source is already less than or equal to the Tier II goal,	тах сопсет	5 - Plumes were predicted to grow when the predicted decay length exceeded 125% of the existing plume length.	sted decay le	he predicted	8 - Longitudinal dispersivity was taken as 53 feet, which is the mean of the Tier II plume lengths, divided		some plum	ly state plun	s not predict	13 - Bulk attenuation half-life describes the chemical's persistence after it has left the source area.	14 - Test case data from Buscheck and Alcantar (1995, p.115) to verify biodegradation rate calculations.	15 - RFCA Annual Groundwater Monitoring Reports have used effective porosity as 0.1
ical	Note 14, Test Case1	Note 14. Test Case2	Note 14. Test Case3	Note 14, Test Case4	Note 14, Test Case 5 -0.06600	mical				on represent	ume end at	on near the	ate that the	the predict	in the predix	tate when the	as 53 feet, w	ě	sed because	quires stead	the plume is	the chemic.	Alcantur (19	oring Repor
Chemical	Note 14.	Note 14	Note 14	Note 14	Note 14	xample che				concentrati	ngradient pl	concentrati	times indic	grow when	shrink whe	t at steady a	was taken	wollos follow	were not u	equation re	da because	fe describes	check and,	vater Monit
Time Period	ľ	-	ľ			2002-2003 example chemical	_			maximm	of the down	1 maximum	zero decay	predicted to	predicted to	sumed to b	dispersivity	9 - Mean of above plume lengths follows:	ispersivities	ion lambda	rate of lamb	ation half-li	ita from Bus	nal Grounds
	-	-	١.	+		7	<u> </u>	-	ŗ	tabulated	distance	tabulated	stive and	ocs were	les were	nes are as	gitudinal	n of abov	ividual d	xdegradat	ugh estin	lk attenus	A case da	CA Amı
PSA Flow-		1	,	ľ	ľ	2 4			Footnotes	- <u>1</u>	2 - Path	3-The	4 - Nega	5 - Plum	6 - Phum	7. Phun	8 - Long	9 - Mea	10 - Ind	11 - Bio	12 - Rot	13 - Bul	14 - Tes	15 - RF
	_	_	_	_	_	_						_	_			_			_	_		_		_

			ì	•							
	Α	В	C	D .	E	F	G	Н	I	J	K
The state of the s	PSA	Flow-path	Time Period	Chemical	InC vs D Slope (per ft)	Tier II C Goal ug/L	Kd ml/g	UHSU Effective Porosity (n)	UHSU Bulk Density Rho g/ml	Well # on path at Max Conc Near Inferred Source	Max Conc ug/L of Well Near Source During Time Period
2	-	-	} -	Note 14, Test Case 1							3660
3			-	Note 14, Test Case2	-0.066						3660
4	-	-	] -	Note 14, Test Case3	-0.066						3660
5	-	-	] -	Note 14, Test Case4	-0.066						3660
6	-	-	-	Note 14, Test Case5	-0.066						3660
7	2	A	2002-2003	example chemical	-0.0026	7	0.093	0.1	2.1	13191	34.1
8			Ì								
9											



	L	М	N .	0	P	0	R	S	Т
1	Measured Path Distance of Well Near Source at Max Conc. (ft)	Estimated Path Distance of Tier II Down-gradient Plume End (ft)	Foot- notes	Water Velocity (ft/yr)	COC velocity (ft/yr)	Bulk Atten. Rate k (per yr)	Bulk Attenu-ation Half-life (yr, note 13)	R	decay time (yr) to meet Tier II goal (see note 4)
2				0.06	=O2/S2	=E2*(-1)*P2		2	
3		, i		0.03	=O3/S3	=E3*(-1)*P3		2	
4				0.06	=O4/S4	=E4*(-1)*P4		2	
5		1		0.06	=O5/S5	=E5*(-1)*P5		1	
6	***************************************			0.06	=O6/S6	=E6*(-1)*P6		1	
	165.35	340		94.5	=O7/S7	=E7*(-1)*P7	=0.6931/Q7	=G7*I7/H7+1	=(-1)*LN(F7/K7)/Q7
8					ļ				
9	<u> </u>	i.				1			



	U	V	W	X
1	Predicted Decay Length (ft) from Well with Max Source	Estimated Existing Plume Length (ft) from Well with Max Source	The plume is predicted to grow or shrink after time period of Column C (notes 5,6,7)	Biodegradation rate constant (1st order lambda, per yr., note 11)
2			steady	=IF(W2="steady",AD2*AC2,"")
3			steady	=IF(W3="steady",AD3*AC3,"")
4	·	f .	steady	=IF(W4="steady",AD4*AC4,"")
5		7	steady	=IF(W5="steady",AD5*AC5,"")
6		Į.	steady	=IF(W6="steady",AD6*AC6,"")
7	=IF(P7*T7<=0,0,P7*T7)	=M7-L7	=IF(U7-1.25*V7>0,"grow",IF(U7-0.75*V7<0,"shrink","steady"))	=IF(W7="steady",AD7*AC7,"")
8				
9				

	Y	Z	AA	AB	AC	AD
1	Rough estimate of biodegradation rate constant (plume not at steady state, note 12)	Biodegradation half-life (yr.)	longitud-inal disper-sivity (ft)	I INDER DART AT /DA	second term	first term
2	<u>,                                    </u>	=IF(W2="steady",0.6931/X2,"")	7.5	=1-(2*AA2*E2)	=(AB2*AB2)-1	=P2/(4*AA2)
3		=IF(W3="steady",0.6931/X3,"")	7.5	=1-(2*AA3*E3)	=(AB3*AB3)-1	=P3/(4*AA3)
4		=IF(W4="steady",0.6931/X4,"")	15	=1-(2*AA4*E4)	=(AB4*AB4)-1	=P4/(4*AA4)
5		=IF(W5="steady",0.6931/X5,"")	7.5	=1-(2*AA5*E5)	=(AB5*AB5)-1	=P5/(4*AA5)
6		=IF(W6="steady",0.6931/X6,"")	0.3	=1-(2*AA6*E6)	=(AB6*AB6)-1	=P6/(4*AA6)
7	=IF(W7 $\diamond$ "steady",AD7*AC7,"")	=IF(W7="steady",0.6931/X7,"")	52.6	=1-(2*AA7*E7)	=(AB7*AB7)-1	=P7/(4*AA7)
8	;					
9						

_	
5	

Plume exceeds goal and continues to increase																				_
	819		£9.£		28£10.0-		0.202				1250.0			0.125		0.00010		2002-2003		7 Z I
COC may exceed goal in the future and become a plume COC may exceed goal in the future and become a plume	0		50'7	6.2-	-0.24183		0.202				24.0	007.10				0.00230	cis-1,2-DCE			7 Z I
	<u> </u>		Σ0'Z	Z.1-			0.202				0.8			100.0		06500.0		1002-2003		A 01
· · · · · · · · · · · · · · · · · · ·			£6.£				Z.42.				0.EE	2,10 41299		0.125		07200.0		6661-8661		VOI
			28.T			p.7	2.42				0.062					0.00140		6661-8661		V 01
COC may exceed goal in the future and become a plume			2.45	1.96-		1.22	2.42				<b>₽.</b> £	2.10 P416889				08000.0		6661-8661		V OI
COC may exceed goal in the future and become a plume	0		2.49	p.11-		8.12	2.42				0.84	2.10 41299	1.0			08200.0	cis-1,2-DCE			VOL
COC may exceed goal in the future and become a plume	0	8£1	2.03	£.71-	70040.0-	<i>1</i> .92	2.42	٤	6.1881	6.1851	4.0	2.10 P416889	1.0	610.0	100	05100.0	CE	6661-8661	٧	V OI
	0	121	2.22	8.11-	29820.0-	24.4	54.2	٤	0.478	0.478	0.£	2.10 41299	1.0	820.0	3650	0,00240	1,1-DCA	6661-8661	V	A OI
COC may exceed goal in the future and become a plume			<b>₽</b> 2.9	p.p3-		£.8	5.4.2				4.0	2.10 P416889	1.0			0.00130	1,1,1-TCA			A 01
			£9.£	4.04-		0.21	5.42				8.02	2,10 41299				00100'0		1002-0002		V 01
			4.32	4.81-			2.42				0.01					0.00300		1002-0002		10 A
			2.49			8.12	2.42			0.478	2.22	2.10 41299				06200.0	eis-1,2-DCE			A   01
COC may exceed goal in the future and become a plume			2.03	2.3-			2.42			9.1851	2.2	2.10 P416889				0.00400		7000-7001		10 V
COC may exceed goal in the future and become a plume Plume exceeds goal and continues to increase	11		€9.€	6.72-		0.21	2.42			0.478	8.25.8	5'10 41599	1.0			08000.0		5002-5003		A 01
COC may exceed goal in the future and become a plume	0		2.03	4.4ſ-		7.75£	5.4.3			7.288 7.4.0	0.4 9.4	2,10 0374	1.0			08100.0		1661-0661		V L
	0		£0.2	£.1-		2.TIE	£.433				0.8	2,10 12191	1.0 ]			07100.0	Trans-1,2-DCE			VL
	<u> </u>		2.45	L.1-		271.3	£199				121.4	2,10 03391	1.0			0.00150		1992-1993		VIL
	845		4.32	1.0-		8.621	5.433				0.080€	2,10 24193				04900.0		1992-1993		V L
			2.03	5.0-		p.728	£.433				2.281	2,10,24193				08500.0		1992-1993	·	VL
	-	-	2.95	2.6-		0.225.0	£.433				0.42					02000.0		1992-1993		VL
			Þ5.8	4.5-		2.101	£.433			0.222	2.201	2.10 24193			_	0.00200	1,1,1-TCA			٧L
Plume exceeds goal and continues to increase	115	65-	€9.€	<b>6.81</b> -	\$99£0.0-	£.£81	€.438			0.68T	£.E4	16811 01.2				0.00020	TCE	L661-9661	٧	٧L
COC may exceed goal in the future and become a plume	0		5.49	6.2-	1004001	L'99Z	€.439	٤	0.687	0.687	0.41	7,10 11891	1.0			06000.0	cis-1,2-DCE			٧L
	0	٤	\$0.5	1.1.		A.TSE	£.433		£.7 <del>8</del> 6	£.7 <del>8</del> 6	20.5	7.10 03691	1.0			06100'0		L661-9661		V L
			4.32	0.1-		8.621	£. <del>1,</del> 99			0.218	8.104	2.10 03391	1.0	881.0		0.00430		2002-2003		٧٧
	0	10	50.2	0.٤-		<b>327.4</b>	£.499			£.78e	2.6	2,10,03691	1.0			07000.0		2002-2003		٧Į٧
	<b>L6</b> Z	ξ-	£9.E	€.0-			0.017				0.5082	2.10 01.74	1.0	0.125		07010.0		1661-0661		٧S
			25.T	5.0-		0.79	0.017			8.204	0.00484	2.10 01.74	1.0	10€.0		0.01520		1661-0661		V S
		ζ.	£9.£	5.0-	68008.2-		0.017			8,204	0.00088	\$710 01.2 \$710 01.2	1.0			0.01820		1661-2661		VS
			24.S 28.F	7.S-			0.017 0.017			8.7£8 8.7£8	7.41	16220 01.2	1.0			06000.0		1992-1993		VIS
	Z9Z	1-	€8.E	Z.O-	81062.6-		0.017			8.753	£.82£		1.0 [			0.01680		1664-1662		V 5
	79E	<del> </del>	28.T	₽.O-		0.76	0.017			8.753	0.2752	16220 01.2	1.0			0.01610		\$661-1661		٧s
			60.S	9.0-		339.4	0.017			₱.E38	7.0	2.10 15699	10			0.00340	trans-1,2-DCE			VS
		·	75.4	<b>p.</b> 0−		164.4	0.017			₽.E38	0.8	2.10 15699	1.0	-		09010.0		6661-8661	-	٧s
		<del> </del>	2.49	4.0-		0.285	0.017			p.£88	£.92£	2.10 15699	1.0	170.0	04	07800.0	cis-1,2-DCE			٧S
			2.03	€.0-		349.9	0.017			p.E98	0.25.0	2.10 15699	1.0 (	640.0		07200.0	CE	1998-1999	V	٧S
Plume exceeds goal and continues to increase	<b>L8</b>	1.	26°Z	2.0-	06692.6-	4.042	0.017	7	0.026	p.£88	6.6T	2.10 15699	1.0	£60.0	L	09£10.0	1'1-DCE	6661-8661	V	٧S
			2.49	ς·ε-		0.285.0	0.017			<b>₽.£</b> 88	2.522	2.10 15699	10			07000.0	cis-1,2-DCE			٧ļ۶
	•	I .	2,03			349.9	0.017			p.£88	1.91	2.10 15699	10			08400.0		1002-0002		٧S
			2.45			3.85	5.46			1.889	¿.7a	2.10 1187	1.0			000000		1661-0661		VE
			€9.€			1.62	5.46			£.£73	0.25083	2.10 07391	10			0.01000		1992-1993		VE
			2£.7	2.7.		15.9	5.46			2.273	5.266	2.10 07391	1.0			02700.0		1992-1993		ΑE
	128	52-	4.32	8.2-	0.24730		5.46			7.575	2300.0	2,10,07391	1.0			0.01130		£661-7661		¥ ξ
	L6	9-	£0.C	4.1-		9.94	5.46			Z.ET0	p.00011	7.10 07391	1.0	<del></del>		09010.0		2661-7661		A E
	LZS	12-	£9.£	0.t-	72441.0- 87244.0-		5.46			S.E78 S.E78	0.00017	2.10 07391	1.0	201.0		0.0110.0		\$661*7661		A E
	78 <u>5</u>	96-	£0.2 ZE.7	4.1- 8.4-	Z7974.0-		2.46 2.46			5.573	p.1731	2,10,07391	101			0.01030		\$661-1661		A E
	708	bb-	2.45	0.81-		3.8£	5.49			T.719	2.72	7821 01.2	1.0	690.0		00100'0		1661-0661		V Z
	*19I		£6.€	5.44-	P3850.0-		5.46			1.88€	\$04.4	16690 01.2	101		S	09000.0		1661-7661		VZ
	0	52	2.49	6.61-	E7140.0-		5.46			8.429	24.9	16690 01.2	1.0 1		04	01100.0	cis-1,2-DCE			٧Z
	0		2.49	£.02-	₽1₽£0.0-		5.46	-		1.719	0.88	7821 01.2	1.0		OL	06000.0	cis-1,2-DCE			٧Z
Plume exceeds goal and continues to increase	785	+	2.49	£.0Z-	₱1₱£0.0-		S.49			L'L16	0.275	7821 01.2	1.0 [	170.0	04	06000.0	cis-1,2-DCE			٧Z
COC may exceed goal in the future and become a plume	0	182	2.22	1.81-	2E8E0.0-		5.46	€'1		1.886.1	4.8	710 0990	1.0		3650	06000.0		2002-2003		٧Z
Plume exceeds goal and continues to increase	190i	Z£66-	€9.€	7.8232-	92000.0-	1'97	5.46		1430.0	1'99£	9.99	7.10 06691	1.0 [	6.125	\$	0.00001	TCE	2002-2002	. V	٧٧
	(pouad	(+									Period		1 }					1		-
	(during time			١.	(.17				(y)	(11)	ami I							1		
	Source	bjrmc		13)	ing (per				Plume End	.эпоЭ хвМ	Buring		1 1				1		1	
	xsM diiw	ресошся я		(yr, note	-isuasiis	(1/\frac{1}{3})	(fVyr)	SOLOG	nradient	Source at	Source	Rho g/ml Source			7 <b>/</b> 8n	(ber g)	1	Period	ured	ا ا
Plume Notes	from Well	bas isog	В	Sil-life	ton ei	velocity	Velocity	-	Down-	Well Near	Исаг	Density Near Inferred	Porosity	gVm bX	C Goal	Slope	Chemical	Time	Flow-	, l
	Length (ft)	II 19iT		-unonA. noits	Rate K <0	202	TSIBW	-100T	Distance of Tier II	To somsteid	115W	UHSU Well # on path Bulk at Max Conc	UHSU		Il rəiT	InC vs D	1	-miT	- WOLE	1
	Plume	spoosxo	1	1	Atten.				Path To sonsteid	Path	Jo √3n	UHSU   Well # on path	HISHII	1			'			
													1 1	1			1		1	
	Existing.	litan		Bulk	Bulk	<b>!</b>			Estimated	Measured	Сопс	1	1 1	l .		1	1 1	1 ,		1

COC may exceed goal in the future and become a plume	0	11.	2.49	1.6-	20£11.0-	E.RE	0.88	l E	Z.413	2.413	0.2	TTIED OUT#2	2.10	1.0 :	170.0	04	0.00320	cis-1,2-DCE	1002-0002	V	71
Plume exceeds goal and continues to increase	38	1-	2.95	5.41-	89740.0-	8.62	0.88	T	0.002	7.131	Þ.T	66181	2.10	1'0	€60.0	L	09100'0	1,1-DCE	1002-0002	V	ÞΪ
Plume exceeds goal and continues to increase	881	87-	2.95	S.TT-	Þ6800'0-	8.62	0.88		0.00€	7.131	0.6	66181	2.10	1.0 -	£60.0	L	0.00030	I,I-DCE	2002-2003		
Plume exceeds goal and continues to increase	LLZ	11-	4.32	l2.1-	045340	116.3	0.202	7	0.0871	2.5841	<b>†</b> 109	86512	2.10	1.0	861.0	S	06£00.0	CI CI	6661-8661		
COC may exceed goal in the future and become a plume	0	0	2.03	€.0-	87820.5-	4.745	0.202		2.5841	2.5841	6.89	86512	2.10	1.0	610.0	001	0.00820	CE	6661-8661	<b>V</b>	71
Plume Notes	Existing Existing Plume Plume Length (fl) from Well with Max Source Guring time (during time	bumg		Bulk Attenu- ation Half-life (yr, note	-igunoire	(IVyr) velocity COC	Water Velocity (fl/yt)	-1007 e2100	Estimated Path Distance of Tier II Down- gradient Plume End (fi)	Measured Path Distance of Well Mear Source at. Max Conc. (f)	ITOM	Well # on path at Max Cone Near Inferred Source	-11G	UHSU Effective Porosity (n)	gVm bX	Tier II G Goal J\gu		Chemical	ərriT boʻriə¶	barp Llow-	AS¶

8- | 10.2 | 1.2- | 88.51.0- | 8.54 | 0.88 | 2.0002 | 7.99 | 2.81

#### APPENDIX E

SENSITIVITY ANALYSIS OF BIODEGRADATION RATE CONSTANT CALCULATIONS

#### Appendix E

#### Sensitivity Analysis of Biodegradation Rate Constant Calculations

A sensitivity analysis was performed for the biodegradation rate constants computed in this report using the 1D method of Buscheck and Alcantar (1995). Their method predicts the biodegradation rate constant based on estimates of longitudinal dispersivity, contaminant velocity, and the regression slope of the ln C-vs-D plot. Contaminant velocity equals groundwater velocity divided by the retardation factor (R). R =  $[(K_d * \rho_d)/n_e]+1$  where Kd is the distribution coefficient,  $\rho_d$  is the bulk density, and  $n_e$  is the effective porosity.  $K_d$  is defined as the organic carbon coefficient ( $K_{oc}$ ) times the fraction of organic carbon ( $f_{oc}$ ) in the porous medium ( $K_d = K_{oc} * f_{oc}$ ).

Less easily quantifiable, but perhaps more important, the magnitude of the biodegradation rate constant may be impacted by the following uncertainties:

- Degree of plume stability [i.e., meeting the steady state assumption of Buscheck and Alcantar (1995)];
- Wells projected on the central longitudinal axis of the contaminant plume having CAH
  concentrations in groundwater that may not be representative of those along the axis;
- Uncertainty in plume position and length when monitoring wells do not exist at or beyond the distal end of the plume;
- Uncertainty in source area mass, extent, and location;
- Uncertainty in source area maximum contaminant concentration when wells are not screened in the maximum concentration zone; and
- Lack of VOC monitoring of groundwater from a sufficient number of closely spaced wells along the plume axis to adequately define the slopes of the ln C-vs-D plots.

The choice of calculation method for estimating the biodegradation rate constant also effects its magnitude. The 1D method of Buscheck and Alcantar (1995) is known to overestimate the rate in comparison to the 2D method of Zhang and Heathcote (2003). Further, the 2D method overestimates the rate in comparison to the 3D method (Zhang and Heathcote, 2003). Rationale for the selection of the 1D method was discussed in Section 3.

The following analysis is limited to looking at quantifiable, key parameters that effect the estimated biodegradation rate constants. The ranges of these parameters and their mean values were taken from the 103 plots of ln C-vs-D for which data are tabulated in this report (Appendix D). Sensitivity was determined by computing, in a spreadsheet, the biodegradation rate using the Buscheck and Alcantar (1995) method. Only one parameter was allowed to vary at a time, while fixing all other input parameters at either their mean values, or typical values, as discussed below. The varying parameter was allowed to randomly change by using a random function to estimate it within a data range. The data range used was usually the range of the data corresponding to the 103 plots tabulated in Appendix D. The resulting biodegradation rate constants were plotted against the key parameters and are shown as Figures E-1 through E-5.

Figure E-1 plots the biodegradation rate against the slope of the regression line fitted to each ln C-vs-D path distance plot. The range of slopes shown in Figure E-1 was derived from the actual ln C-vs-D data tabulated in Appendix D. Note that a second order polynomial function very closely describes the biodegradation rate as a function of slope. This is expected because the Buscheck and Alcantar (1995) rate equation includes the slope inside a squared term. However, the second-order curve is quite linear in appearance. Therefore, although the rate is a second-order function of the regression slope, the biodegradation rate is roughly proportional to the slope. Steeper, more negative regression slopes indicate faster CAH attenuation and corresponds to larger biodegradation rates, as expected.

Longitudinal dispersivity was estimated in this report as 10% of plume length and taken as about 53 feet. Figure E-2 shows the estimated biodegradation rate if the dispersivity is allowed to vary between 5 feet and 250 feet. The biodegradation rate appears to be a linear function of dispersivity. However, biodegradation is relatively insensitive to the dispersivity value, and the rate increases slowly when the dispersivity is increased greatly. For example, changing dispersivity by a factor of 10 from 5 feet to 50 feet, changes lambda from 0.30 per year to only 0.35 per year.

The biodegradation rate is a function of the contaminant velocity (Buscheck and Alcantar, 1995). Contaminant velocity is dependent on groundwater velocity and the retardation factor. Figure E-3 shows biodegradation rates as a function of groundwater velocity and indicates that this is a linear relationship. The biodegradation rate appears to be directly proportional to the groundwater velocity (or to contaminant velocity at constant R). Doubling the groundwater velocity doubles the estimated biodegradation rate. Thus, biodegradation rates estimated by the 1D Buscheck and Alcantar (1995) method are very sensitive to the estimated groundwater velocity.

If the biodegradation rate is plotted against the retardation factor, the rate is inversely proportional to R (Figure E-4). This figure also shows that the biodegradation rate is sensitive to small changes in R at R values between 1 and 2. However, the rate is not very sensitive to R values greater than 3, and the sensitivity decreases with increasing R. Changing R from 2.0 to 1.0 approximately doubles the biodegradation rate. Changing R from 6.0 to 3.0 also approximately doubles the rate.

This analysis has shown that biodegradation rates increase in proportion to groundwater velocity and to decreasing retardation factors. Thus, the rates are proportional to the mobility of the CAHs in groundwater. This implies that biodegradation is mainly associated with the contaminant concentration in solution; not the contaminants sorbed on solid phases.

Distribution coefficients are chemical and matrix specific and published values vary greatly. R is directly proportional to  $K_d$  at constant bulk density and effective porosity. Figure E-5 shows how biodegradation rates vary as a function of  $K_d$  (over the range used in this report). The best-fit regression equation is a logarithmic function. The biodegradation rate increases rapidly as  $K_d$  is decreased below 0.05 ml/g. As  $K_d$  increases above 0.1 ml/g, the biodegradation rate is less and less sensitive to changing  $K_d$  values.

In summary, the biodegradation rates estimated in this report are sensitive to a number of external factors such as well placement and available CAH concentration data. Sensitivity analysis suggests that biodegradation rates are relatively sensitive to low  $K_d$  values, but less sensitive at large  $K_d$  values. Biodegradation rates are approximately proportional to the slope of the ln C-vs-D plot, and inversely proportional to R. Changes in dispersivity have relatively little effect on the biodegradation rate constant. Finally, the choice of method for estimating the biodegradation rate, is itself an influence on the magnitude of the rate.

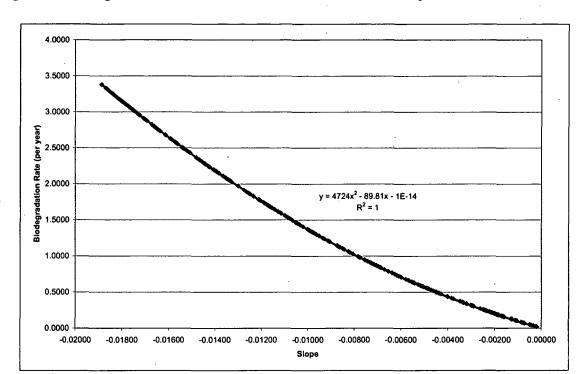


Figure E-1 Biodegradation Rate is a Second Order Function of the Slope of Ln C-vs-D

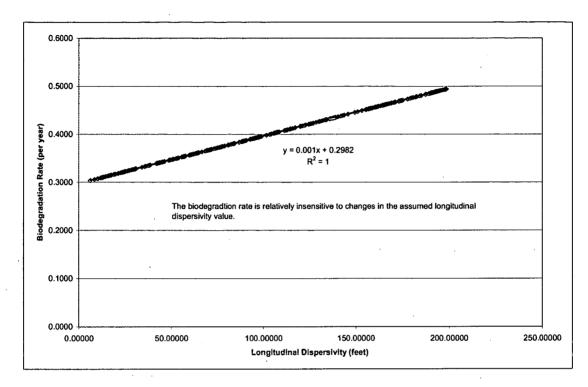
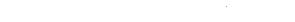


Figure E-2 Biodegradation Rate is Linearly Related to the Assumed Dispersivity



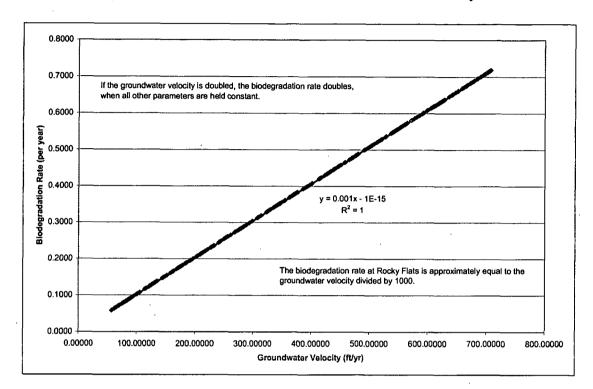


Figure E-3 Biodegradation Rate as a Linear Function of Groundwater Velocity

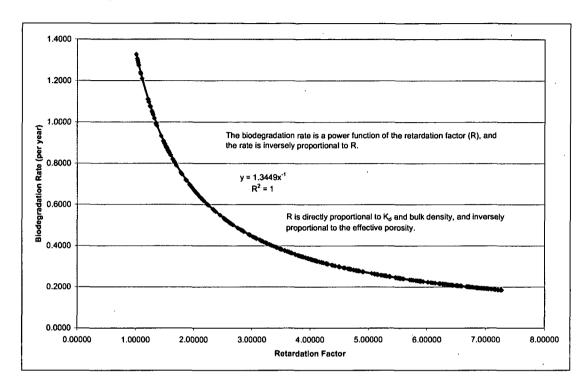


Figure E-4 Biodegradation Rate as a Function of the Retardation Factor (R)

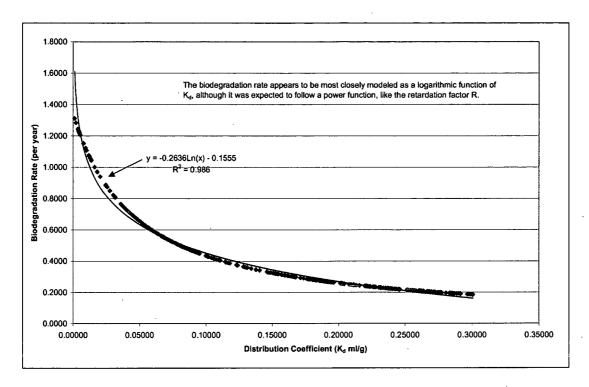
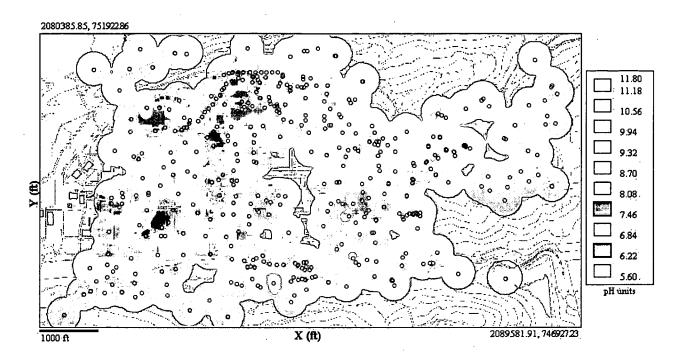


Figure E-5 Biodegradation Rate as a Function of Distribution Coefficient (Kd)

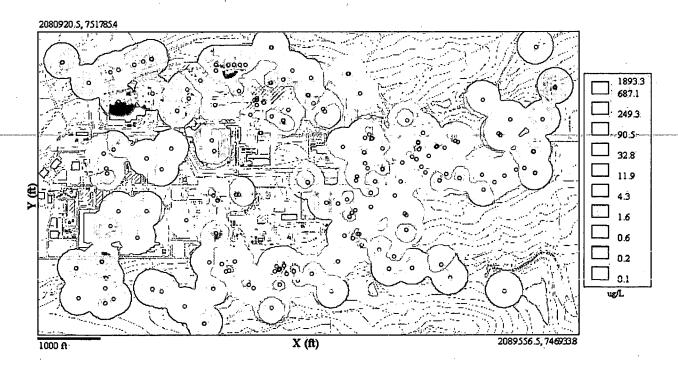
#### APPENDIX F

ISOPLETH MAPS OF THE SPATIAL CONCENTRATIONS OF CAHS, REDOX PARAMETERS AND BIODEGRADATION INDICATOR PARAMETERS DETECTED IN GROUNDWATER

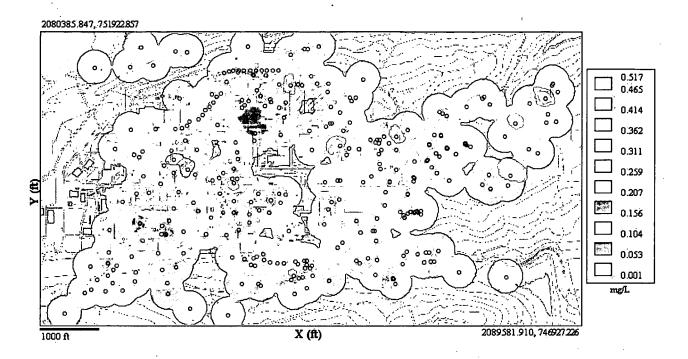
Map of Field-Measured pH in Groundwater During 2002-2003



Map of Maximum BTEX Concentrations in Groundwater at RFETS

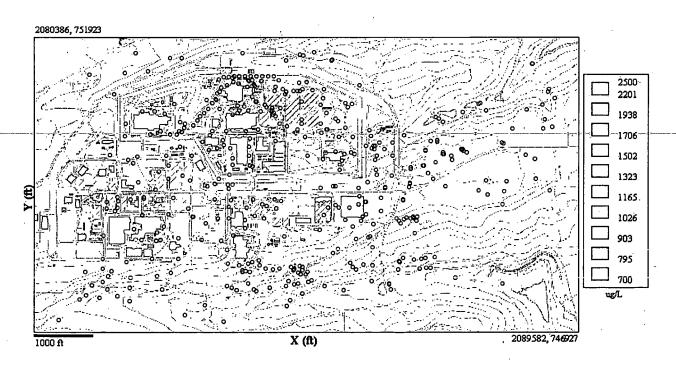


## Map of Sulfide in Groundwater During 2002-2003

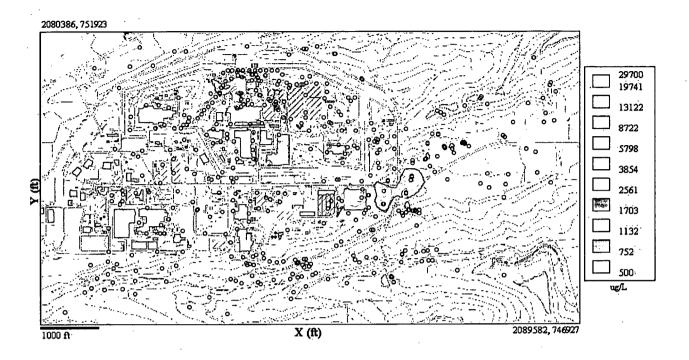


Field All Set2 Sitewide 2002-2003 in Biodegradation.mdb

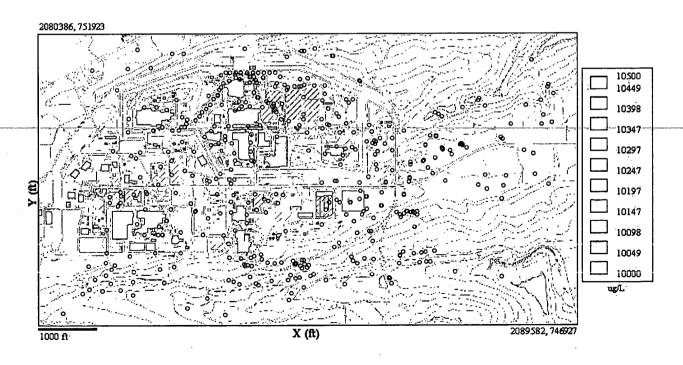
Tier I Plume Map of 1,1-DICHLOROETHENE During 2002-2003



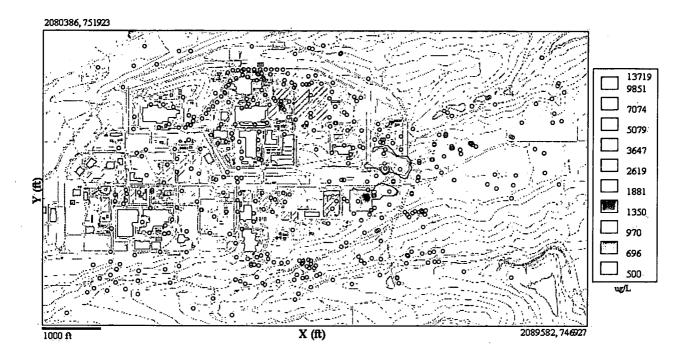
Tier I Plume Map of CARBON TETRACHLORIDE During 2002-2003



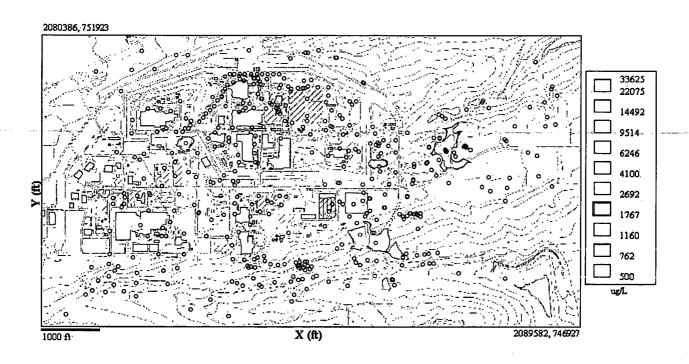
Tier I Plume Map of CHLOROFORM During 2002-2003



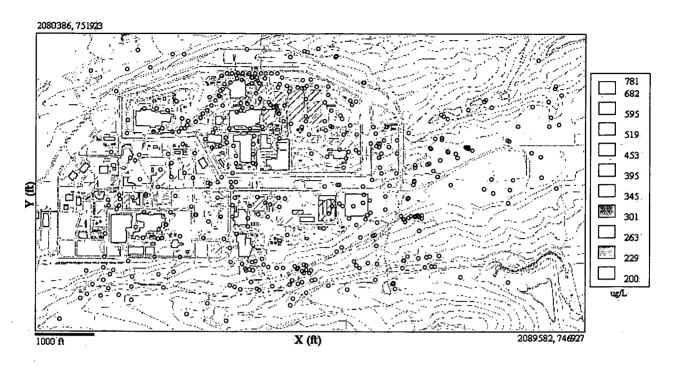
Tier I Plume Map of TETRACHLOROETHENE During 2002-2003



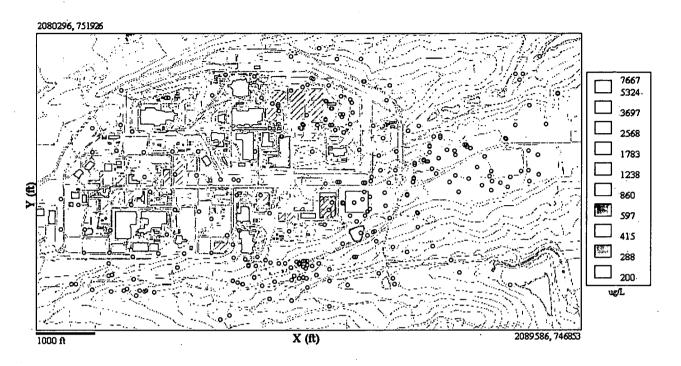
Tier I Plume Map of TRICHLOROETHENE During 2002-2003



Tier I Plume Map of VINYL CHLORIDE During 2002-2003

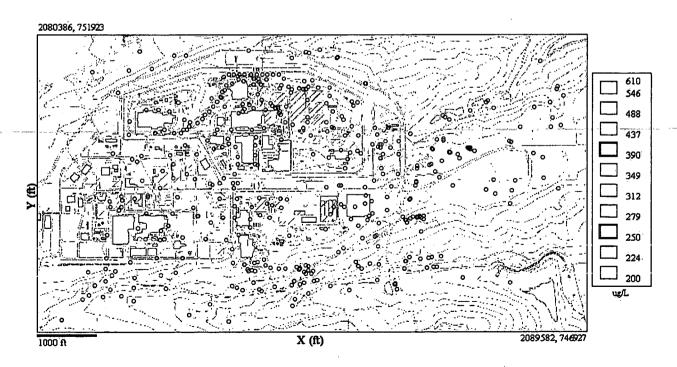


Plume Map of 1,1,1-TRICHLOROETHANE in Groundwater During 1992-1993

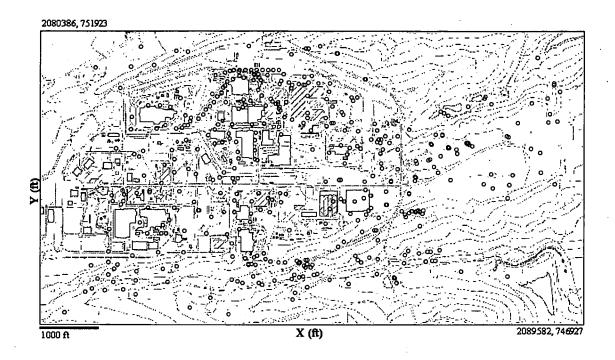


Lab All Set2 Sitewide 1992-1993 in Biodegradation.mdb

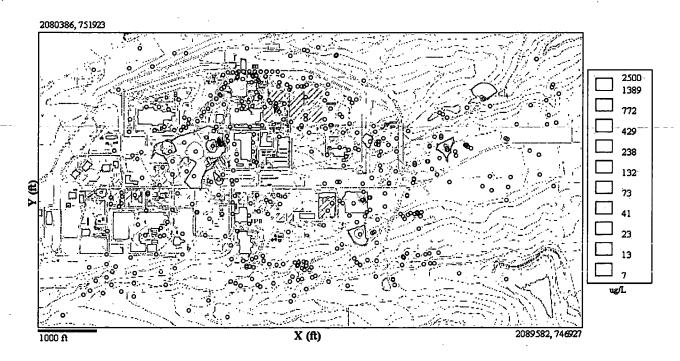
# Plume Map of 1,1,1-TRICHLOROETHANE in Groundwater During 2002-2003



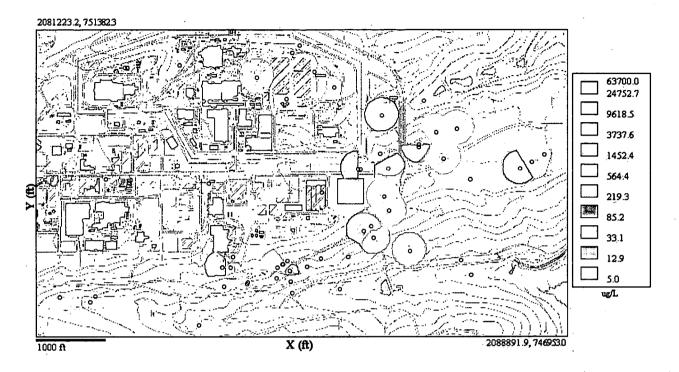
Plume Map of 1,1-DICHLOROETHANE in Groundwater During 2002-2003



# Plume Map of 1,1-DICHLOROETHENE in Groundwater During 2002-2003

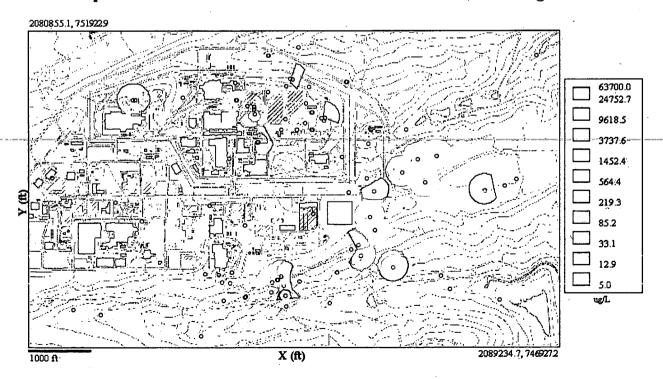


### Plume Map of CARBON TETRACHLORIDE in Groundwater During 1986-1987

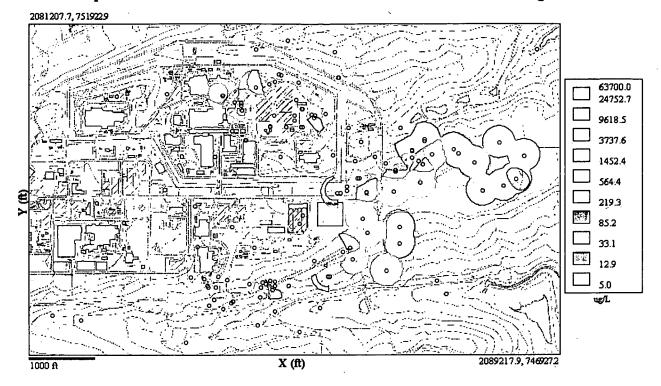


Lab All Set2 Sitewide 1986-1987 in Biodegradation.mdb

### Plume Map of CARBON TETRACHLORIDE in Groundwater During 1988-1989

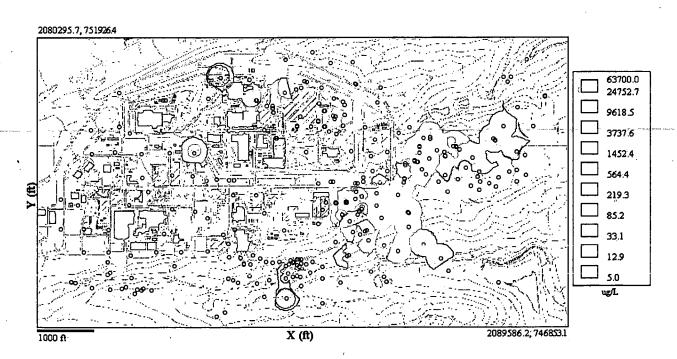


Plume Map of CARBON TETRACHLORIDE in Groundwater During 1990-1991

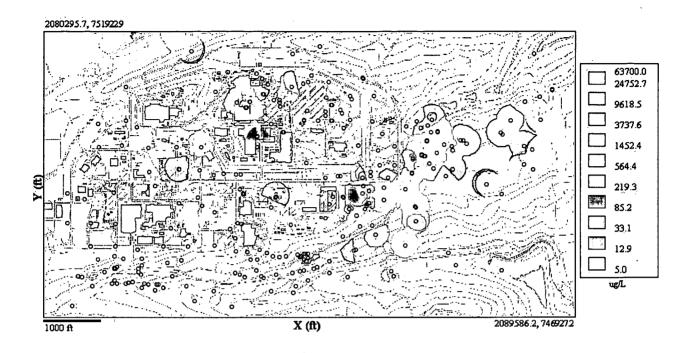


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#### Plume Map of CARBON TETRACHLORIDE in Groundwater During 1992-1993

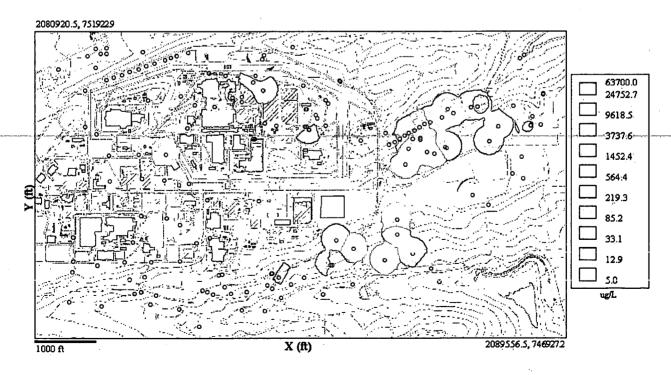


### Plume Map of CARBON TETRACHLORIDE in Groundwater During 1994-1995

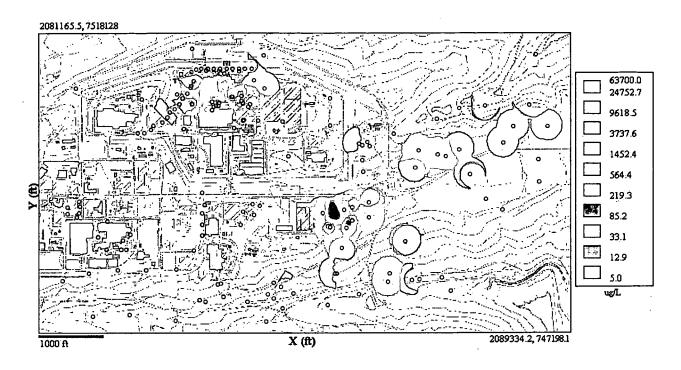


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# Plume Map of CARBON TETRACHLORIDE in Groundwater During 1996-1997

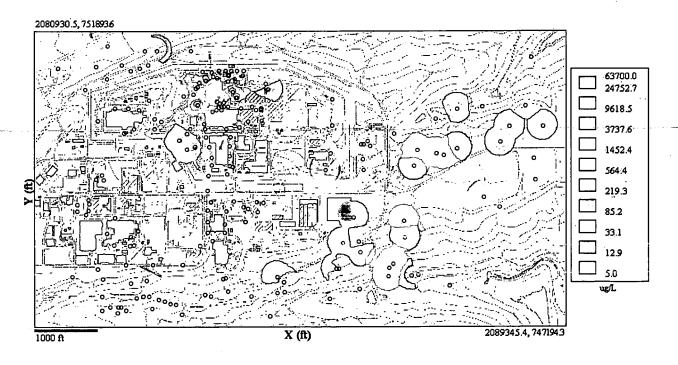


Plume Map of CARBON TETRACHLORIDE in Groundwater During 1998-1999

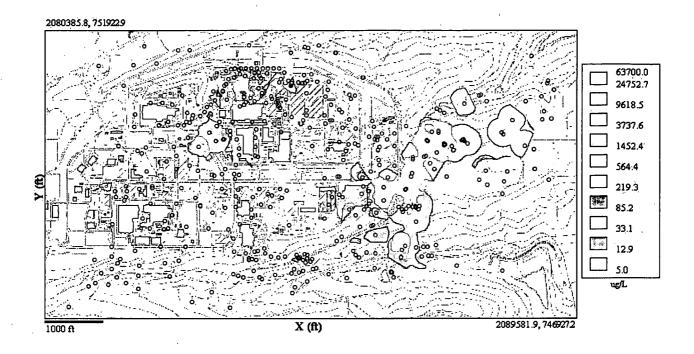


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# Plume Map of CARBON TETRACHLORIDE in Groundwater During 2000-2001

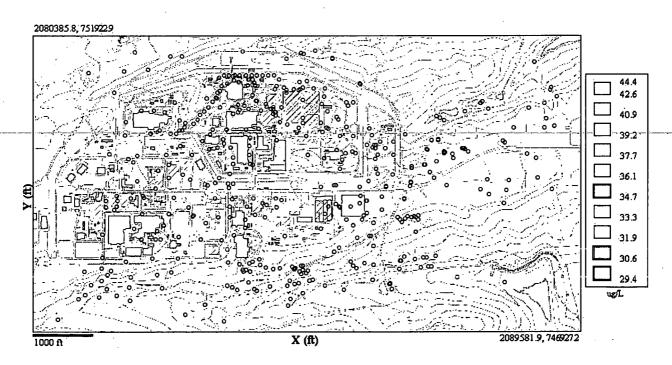


## Plume Map of CARBON TETRACHLORIDE in Groundwater During 2002-2003

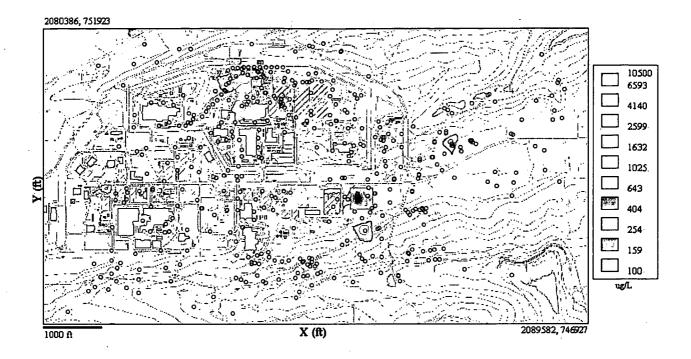


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## Plume Map of CHLOROETHANE in Groundwater During 2002-2003

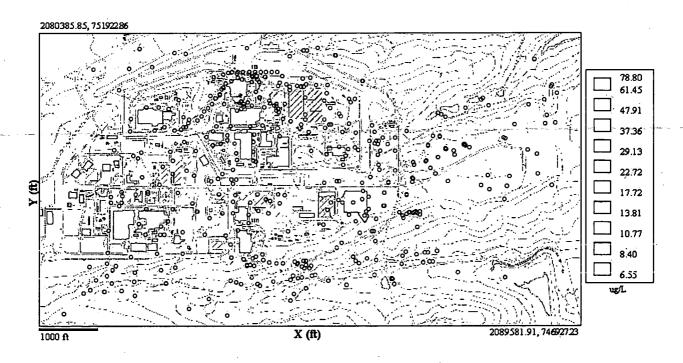


### Plume Map of CHLOROFORM in Groundwater During 2002-2003

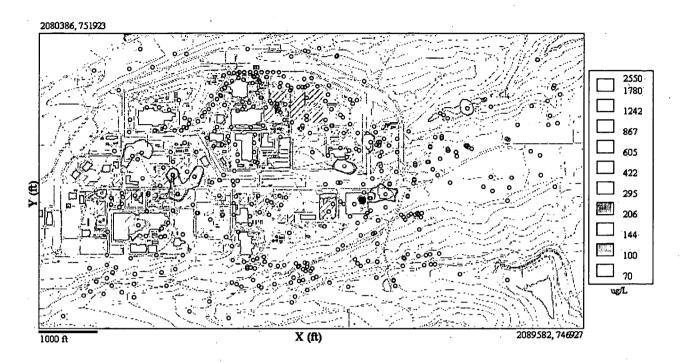


Lab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

### Plume Map of CHLOROMETHANE in Groundwater During 2002-2003

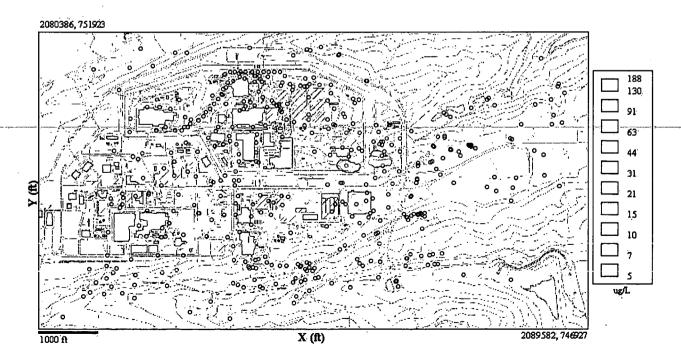


# Plume Map of cis-1,2-DICHLOROETHENE in Groundwater During 2002-2003

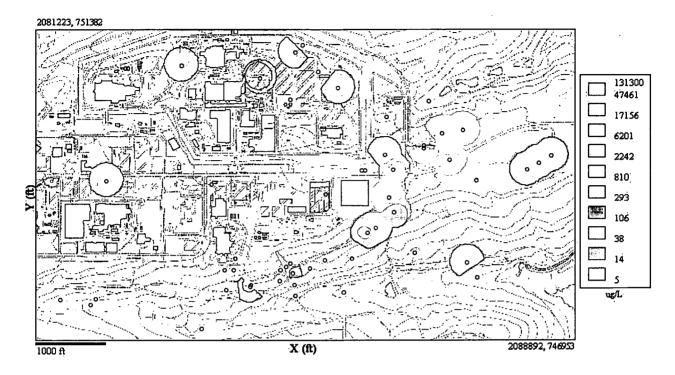


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### Plume Map of METHYLENE CHLORIDE in Groundwater During 2002-2003

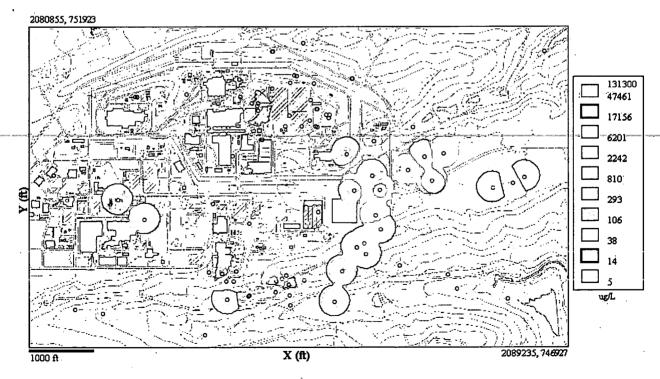


## Plume Map of TETRACHLOROETHENE in Groundwater During 1986-1987

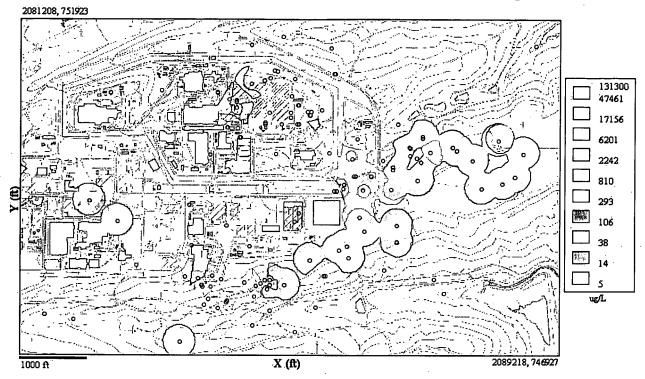


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### Plume Map of TETRACHLOROETHENE in Groundwater During 1988-1989

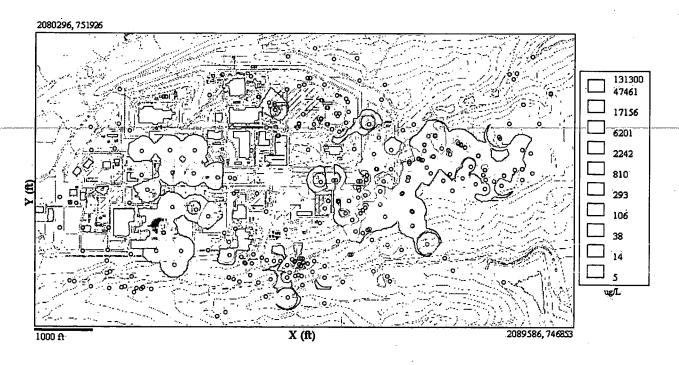


Plume Map of TETRACHLOROETHENE in Groundwater During 1990-1991

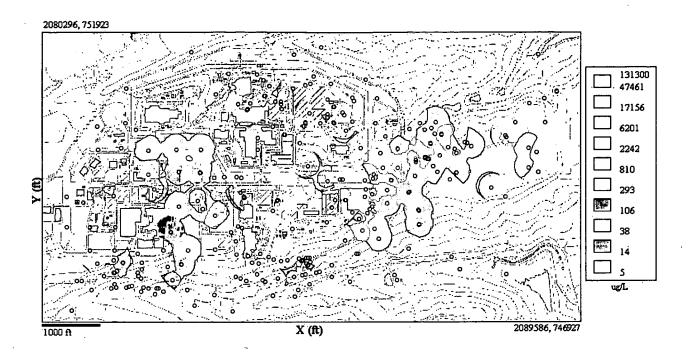


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### Plume Map of TETRACHLOROETHENE in Groundwater During 1992-1993

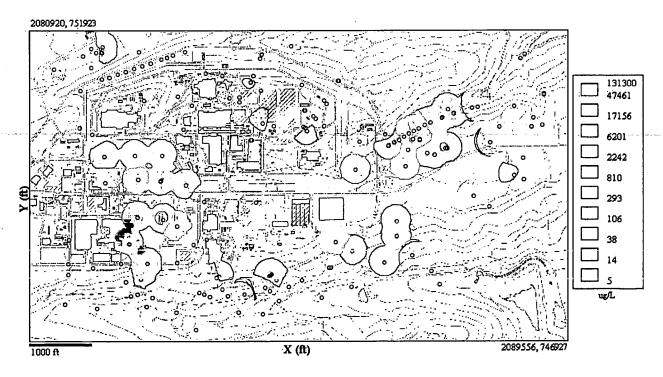


## Plume Map of TETRACHLOROETHENE in Groundwater During 1994-1995

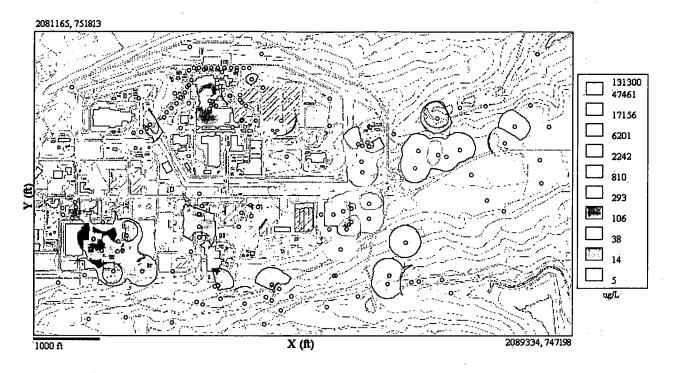


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# Plume Map of TETRACHLOROETHENE in Groundwater During 1996-1997

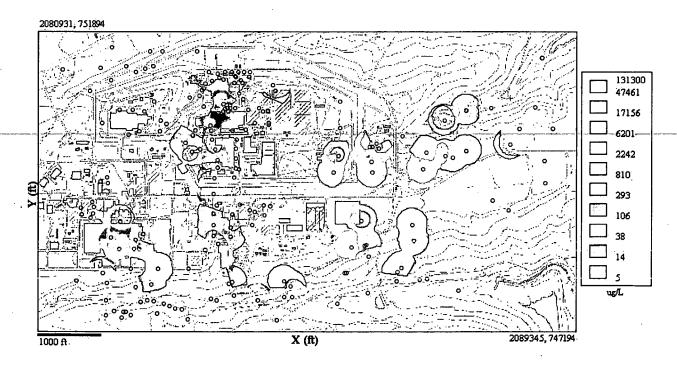


#### Plume Map of TETRACHLOROETHENE in Groundwater During 1998-1999

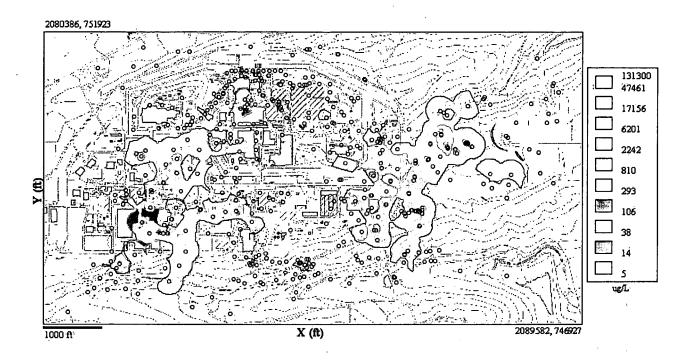


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## Plume Map of TETRACHLOROETHENE in Groundwater During 2000-2001

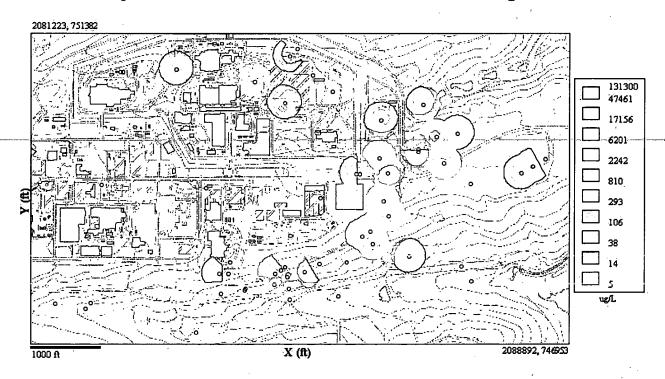


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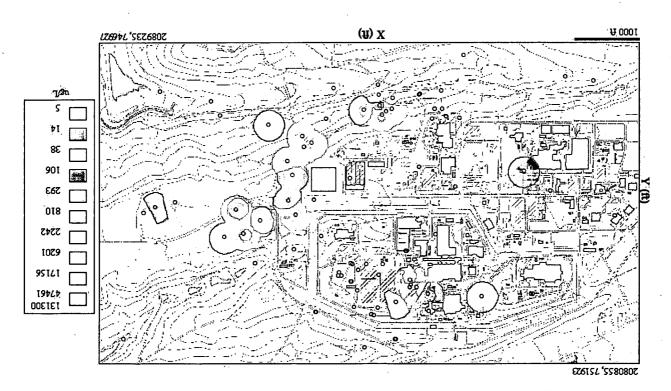
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### Plume Map of TRICHLOROETHENE in Groundwater During 1986-1987



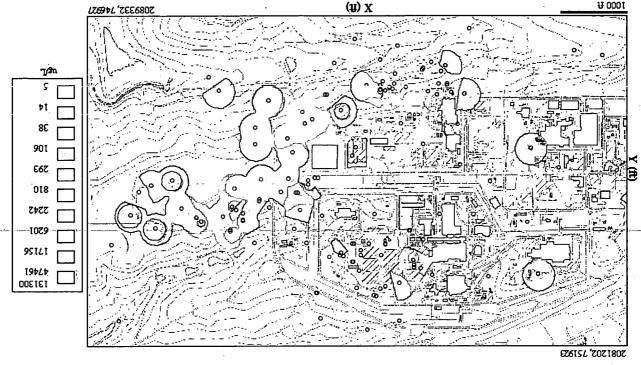
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Plume Map of TRICHLOROETHENE in Groundwater During 1988-1989



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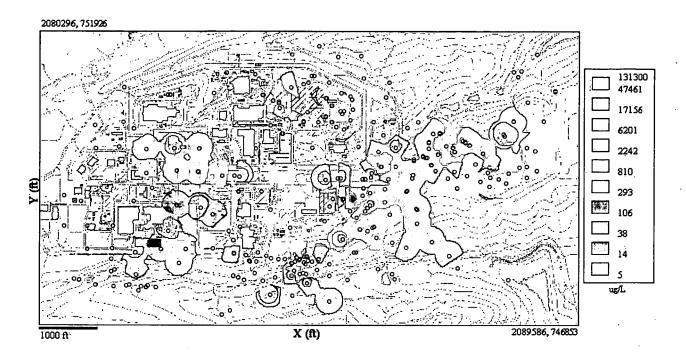
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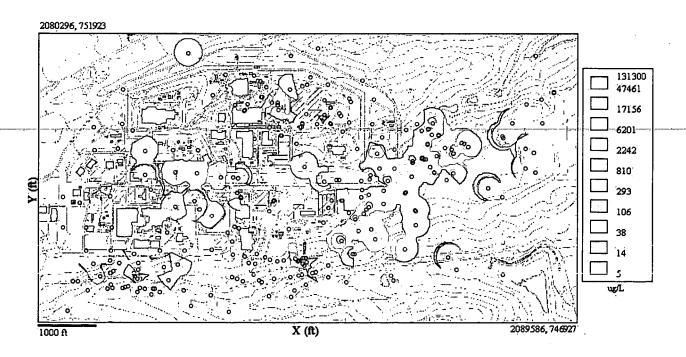
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#### Plume Map of TRICHLOROETHENE in Groundwater During 1992-1993

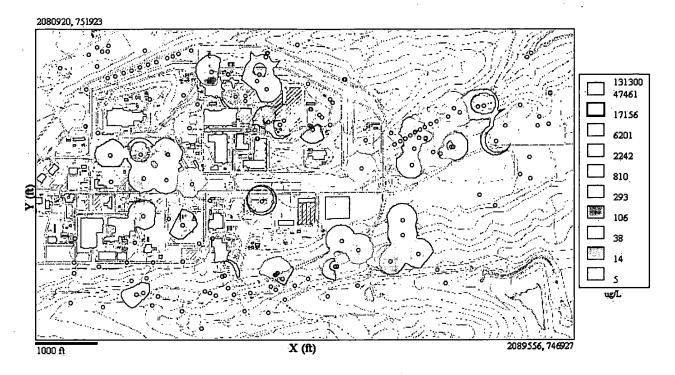


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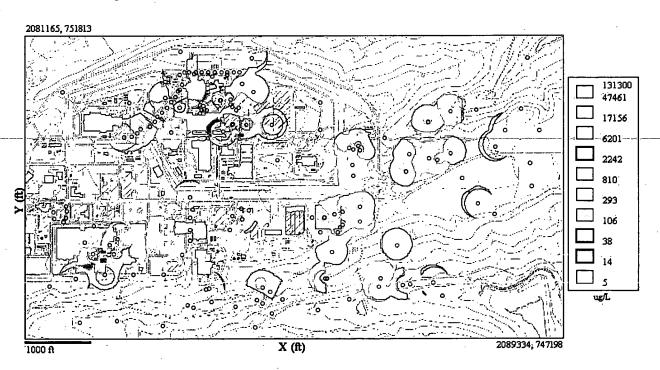


Plume Map of TRICHLOROETHENE in Groundwater During 1996-1997



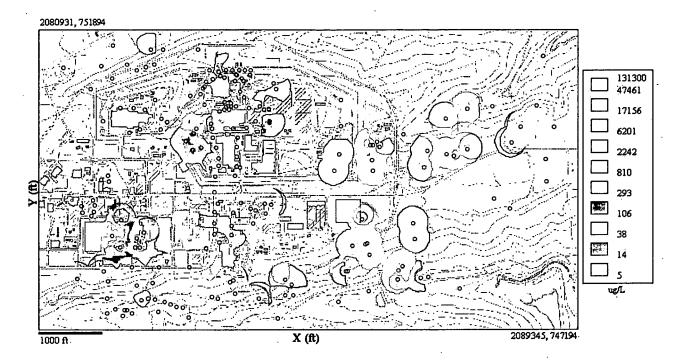
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#### Plume Map of TRICHLOROETHENE in Groundwater During 1998-1999



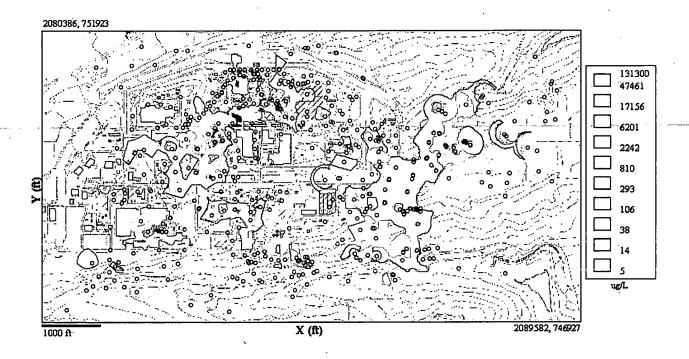
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# Plume Map of TRICHLOROETHENE in Groundwater During 2000-2001

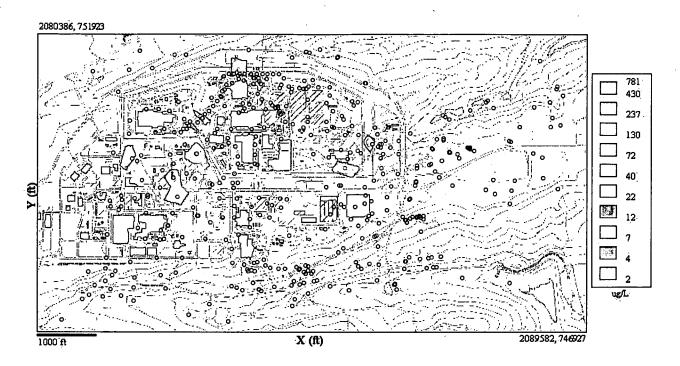


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#### Plume Map of TRICHLOROETHENE in Groundwater During 2002-2003

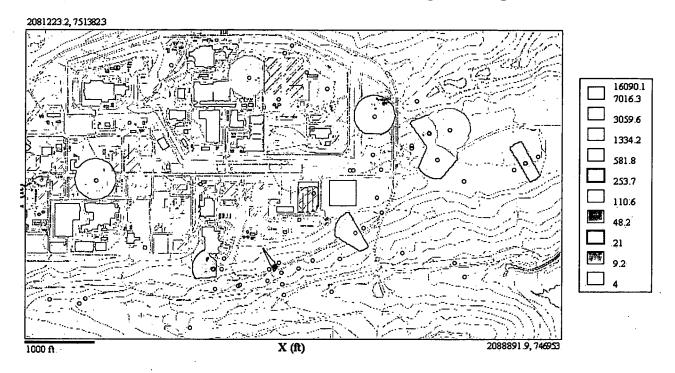


# Plume Map of VINYL CHLORIDE in Groundwater During 2002-2003



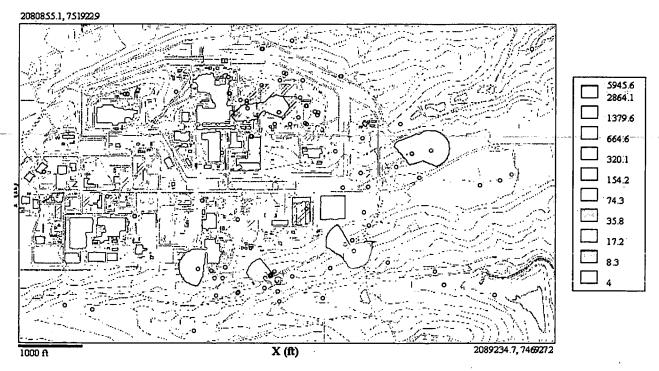
Lab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

## Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1986-1987

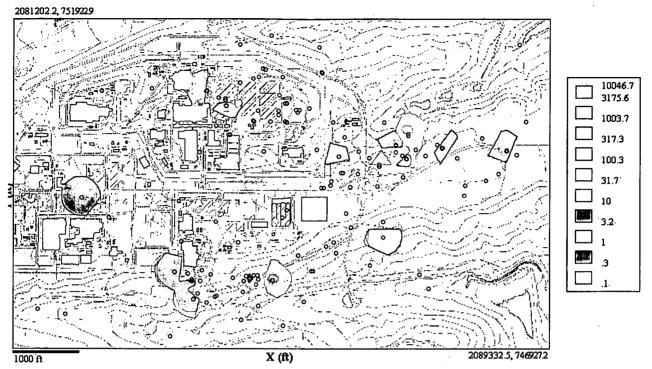


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

## Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1988-1989

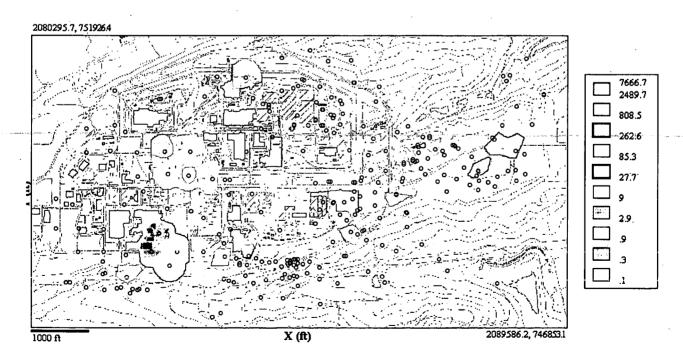


#### Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1990-1991

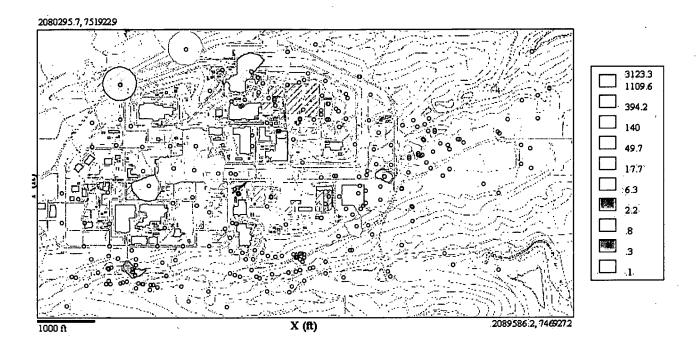


b All Set2 Sitewide 1990-1991 in Biodegradation mdb

#### Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1992-1993

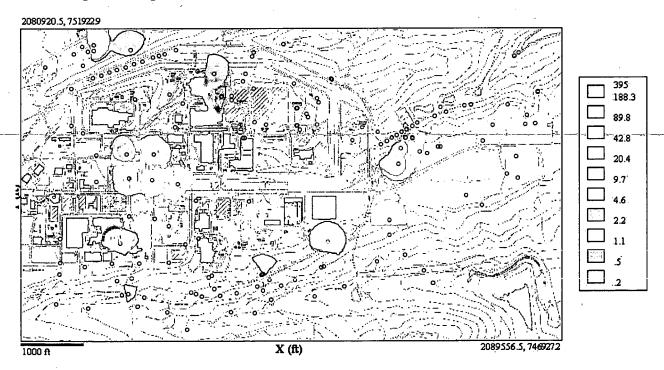


## Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1994-1995



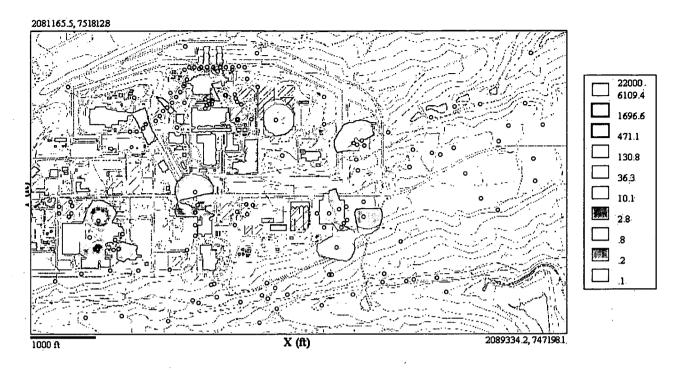
b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

## Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1996-1997



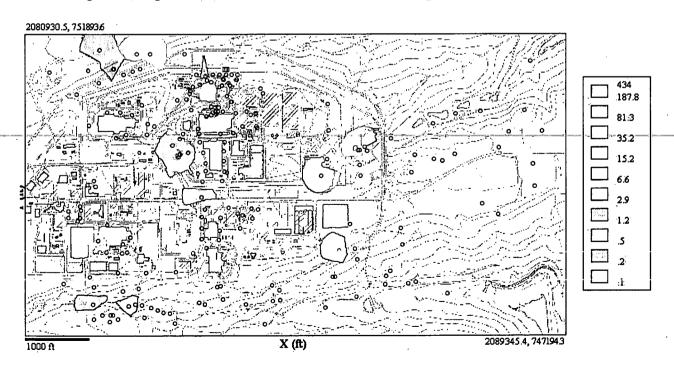
b All Set2 Sitewide 1996-1997 in Biodegradation.mdb

Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 1998-1999

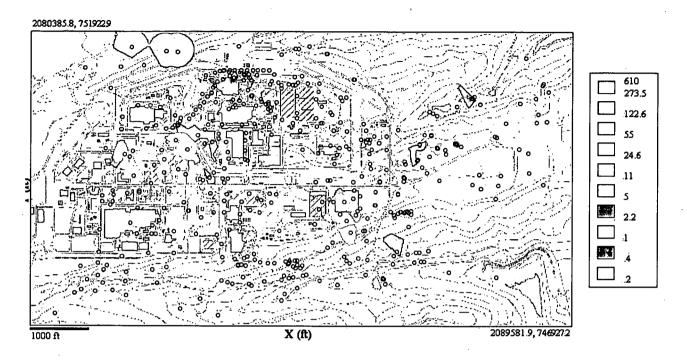


b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

## Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 2000-2001

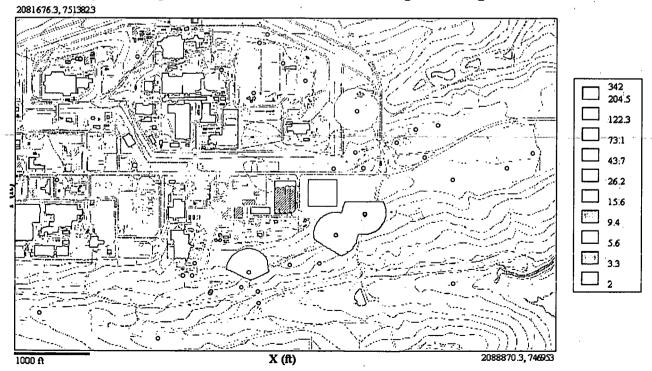


#### Isopleth Map of 1,1,1-TRICHLOROETHANE ug/L During 2002-2003



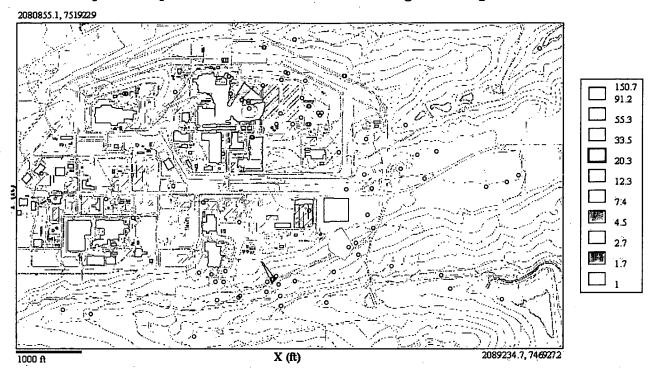
ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

Isopleth Map of 1,1-DICHLOROETHANE ug/L During 1986-1987



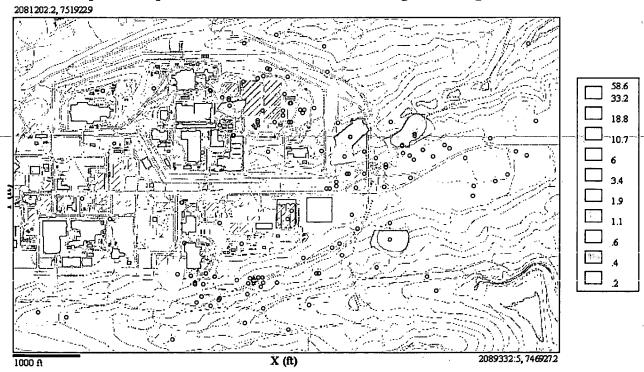
b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

Isopleth Map of 1,1-DICHLOROETHANE ug/L During 1988-1989



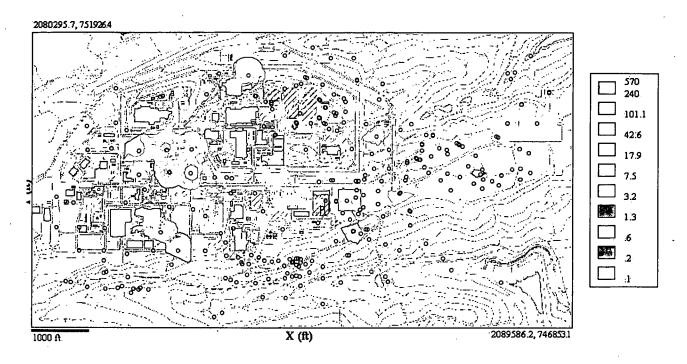
b All Set2 Sitewide 1988-1989 in Biodegradation mdb

Isopleth Map of 1,1-DICHLOROETHANE ug/L During 1990-1991



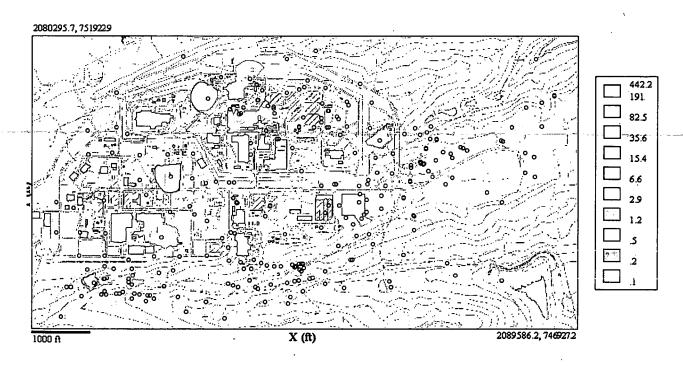
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## Isopleth Map of 1,1-DICHLOROETHANE ug/L During 1992-1993

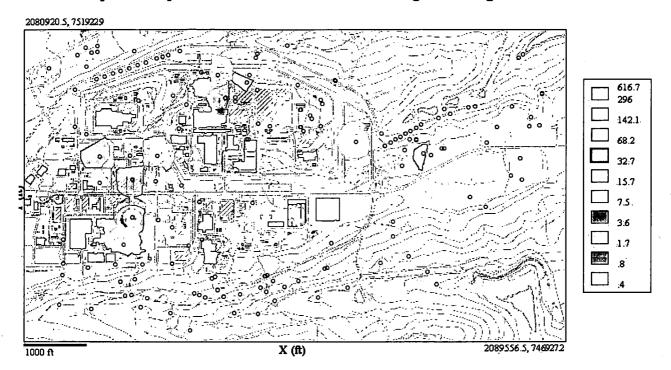


b All Set2 Sitewide 1992-1993 in Biodegradation.mdb

#### Isopleth Map of 1,1-DICHLOROETHANE ug/L During 1994-1995

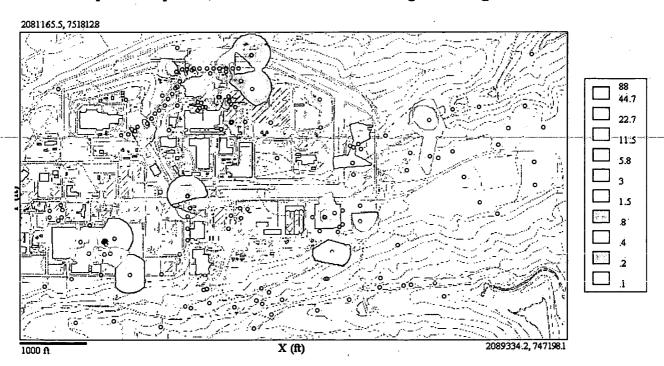


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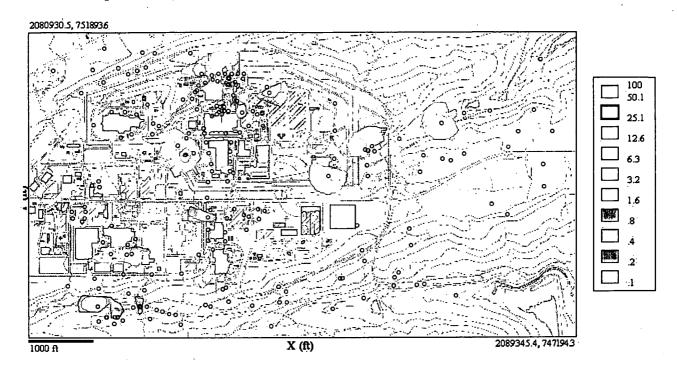


b All Set2 Sitewide 1996-1997 in Biodegradation.mdb

# Isopleth Map of 1,1-DICHLOROETHANE ug/L During 1998-1999

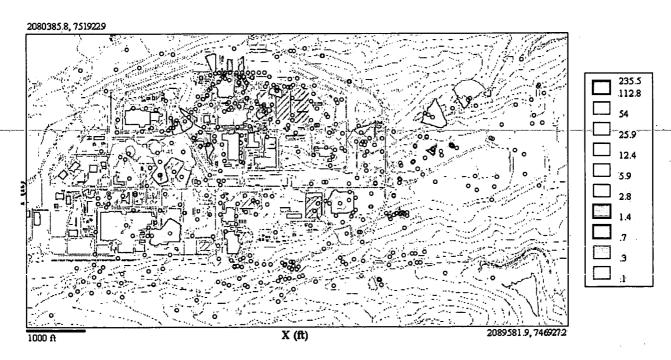


Isopleth Map of 1,1-DICHLOROETHANE ug/L During 2000-2001

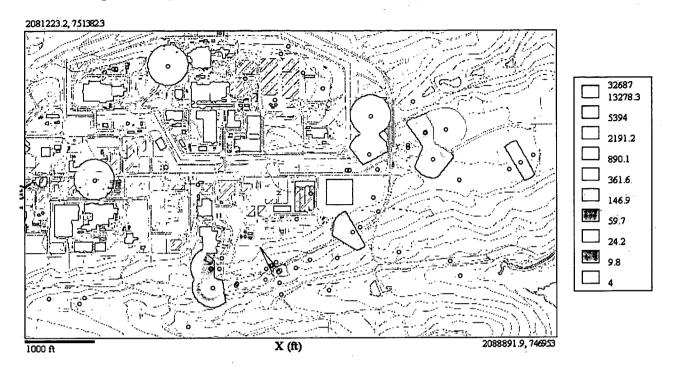


b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

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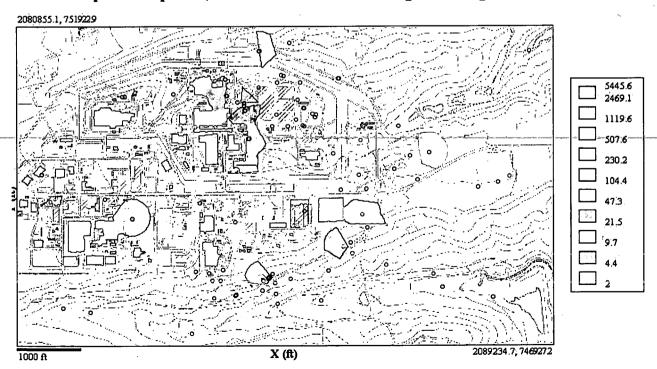


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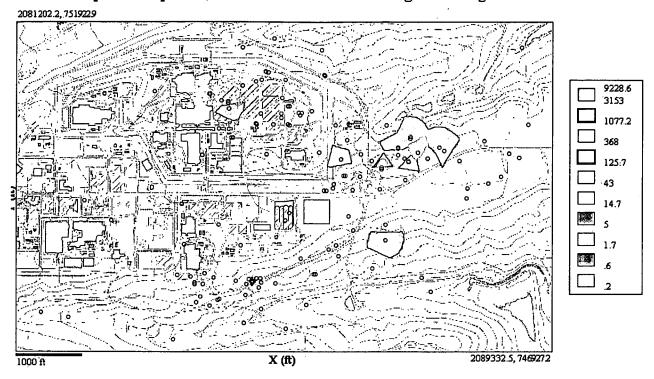


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

Isopleth Map of 1,1-DICHLOROETHENE ug/L During 1988-1989

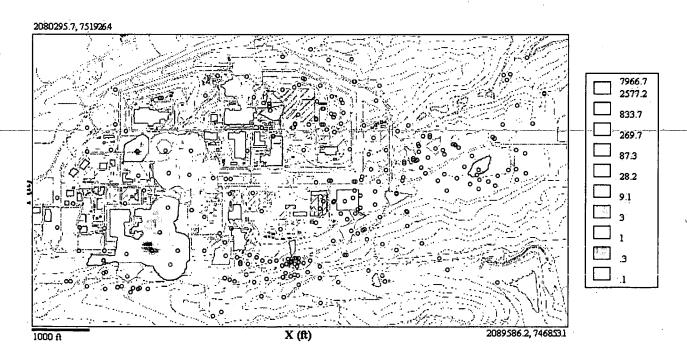


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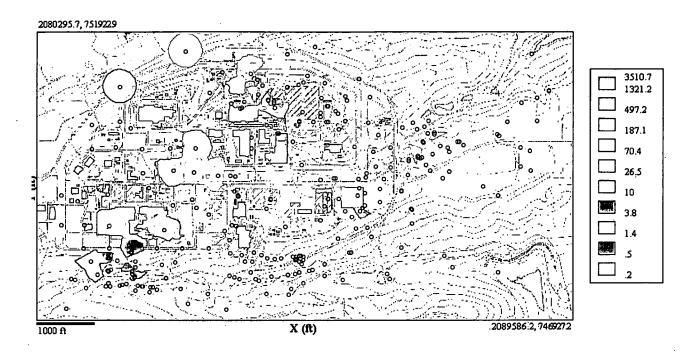


b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

## Isopleth Map of 1,1-DICHLOROETHENE ug/L During 1992-1993

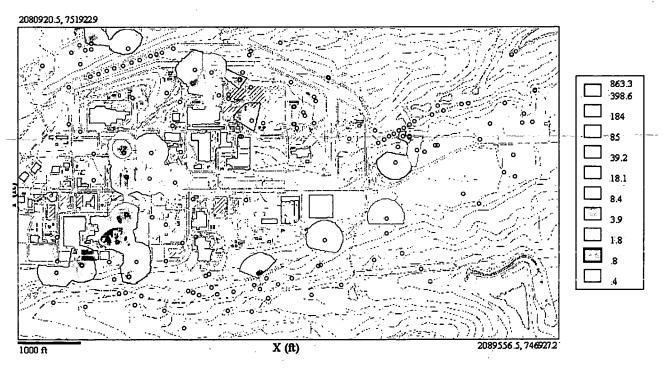


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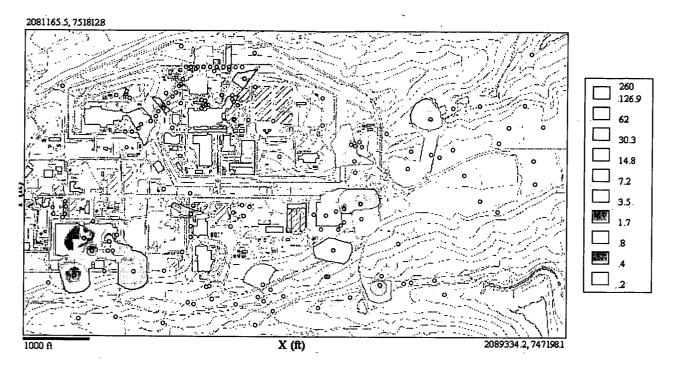


b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

# Isopleth Map of 1,1-DICHLOROETHENE ug/L During 1996-1997

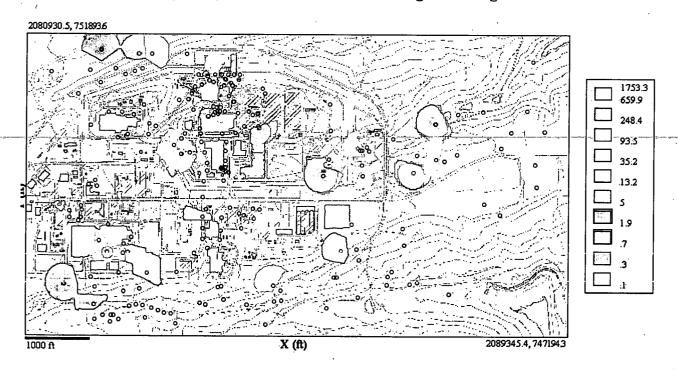


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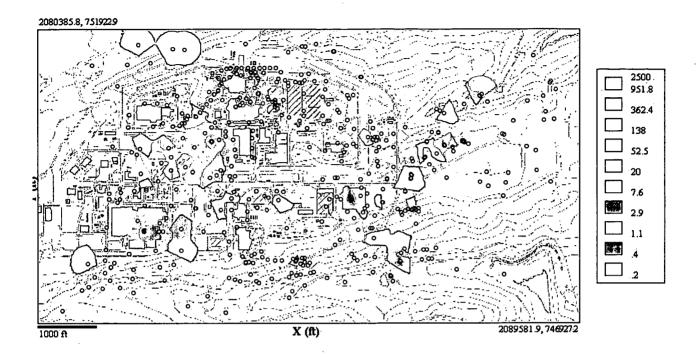
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# Isopleth Map of 1,1-DICHLOROETHENE ug/L During 2000-2001



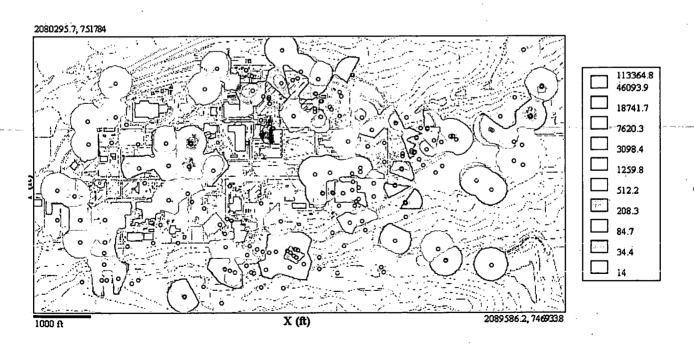
b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

# Isopleth Map of 1,1-DICHLOROETHENE ug/L During 2002-2003

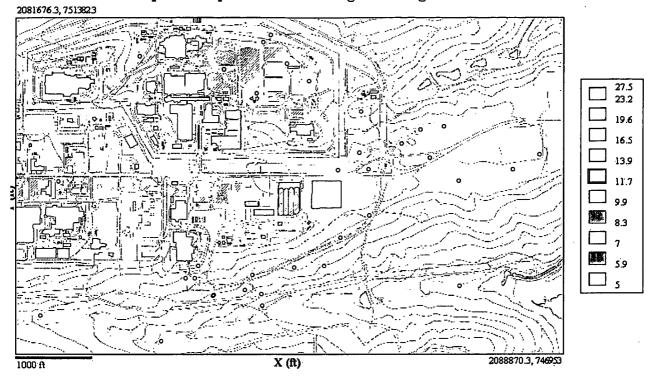


ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

## Isopleth Map of AMMONIA ug/L During 1994-1995

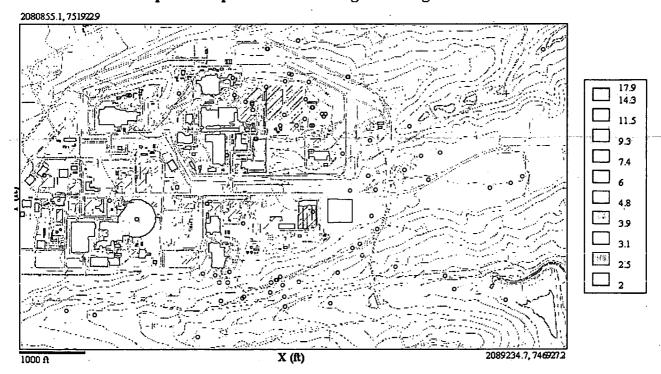


#### Isopleth Map of BENZENE ug/L During 1986-1987

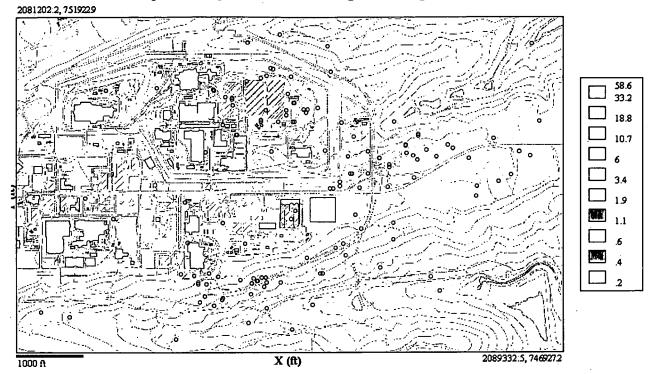


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

#### Isopleth Map of BENZENE ug/L During 1988-1989

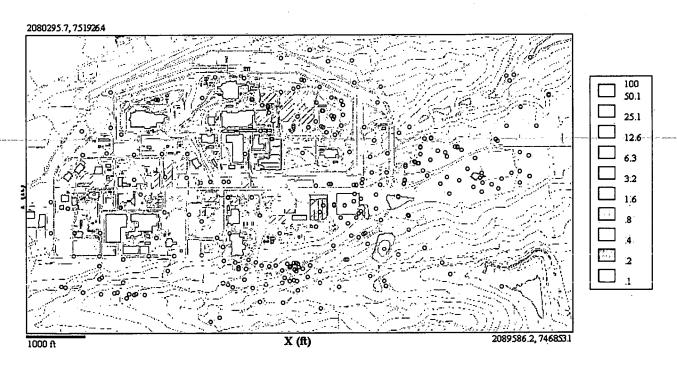


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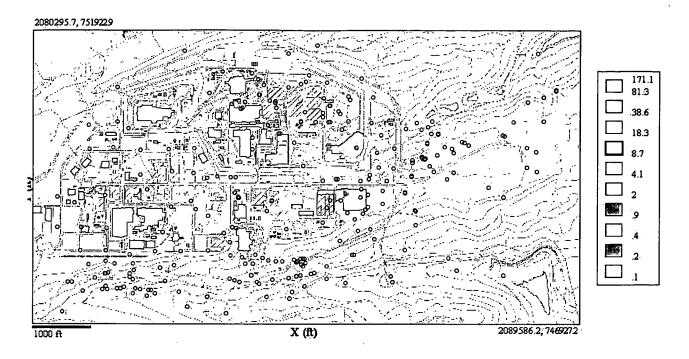


b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

#### Isopleth Map of BENZENE ug/L During 1992-1993

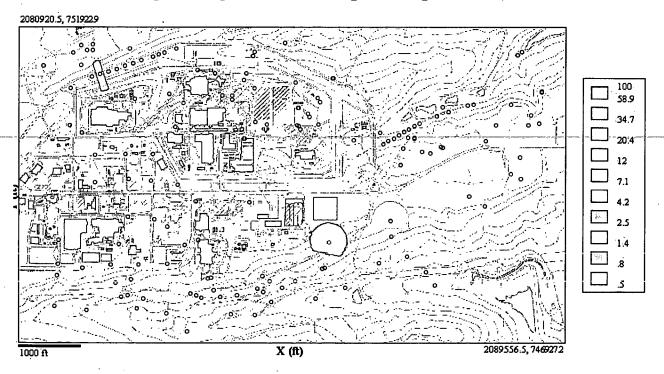


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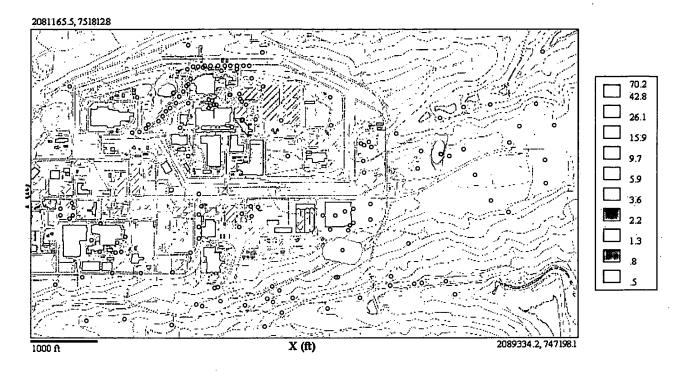


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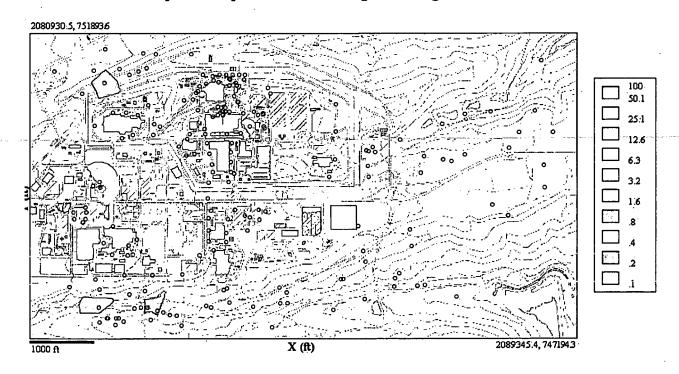


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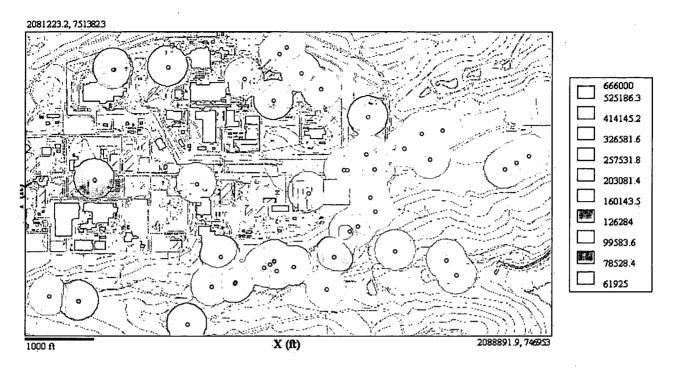


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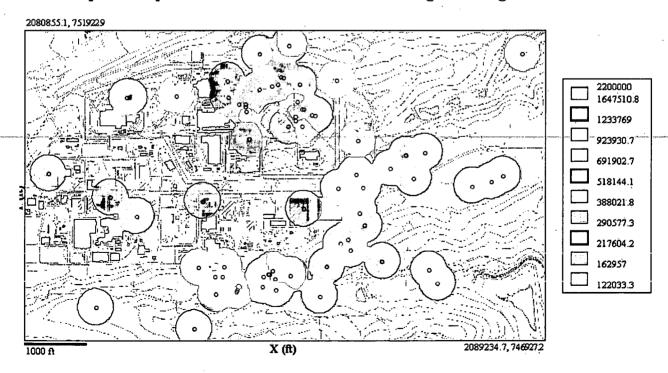


# Isopleth Map of BICARBONATE AS CACO3 ug/L During 1986-1987

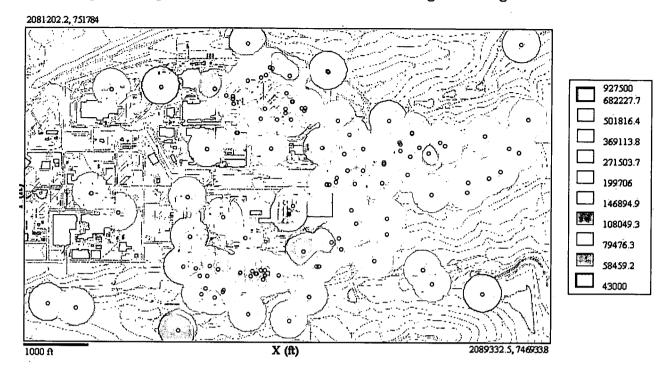


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

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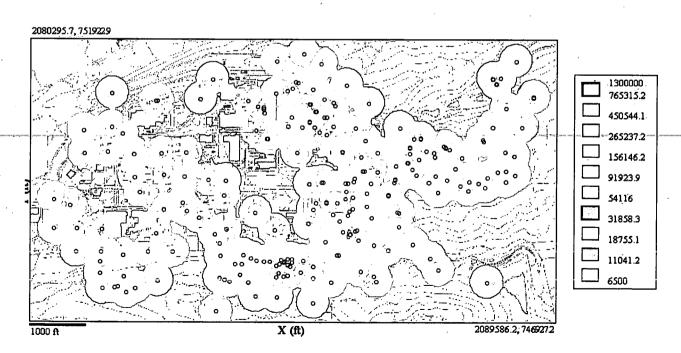


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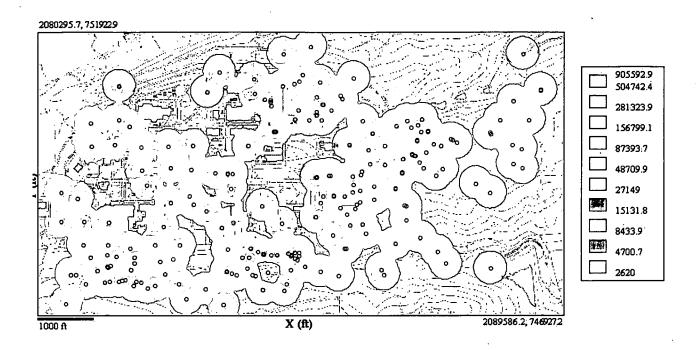


b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

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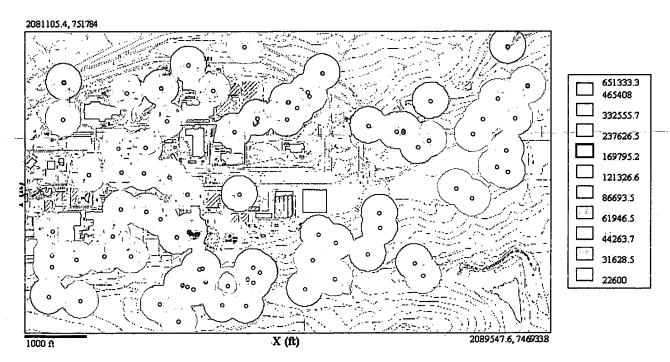


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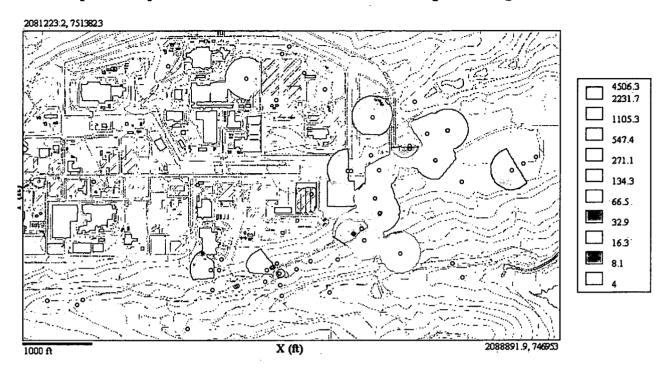


b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

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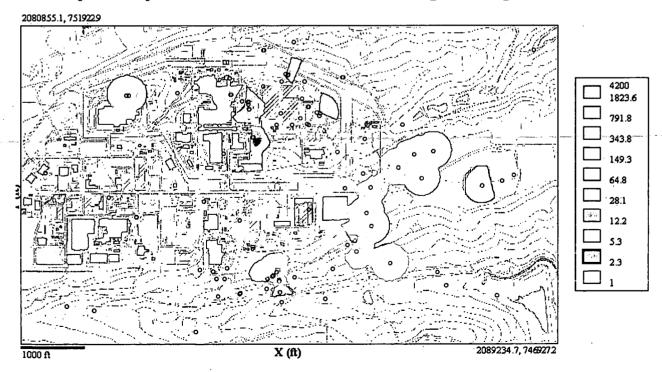


## Isopleth Map of CARBON TETRACHLORIDE ug/L During 1986-1987

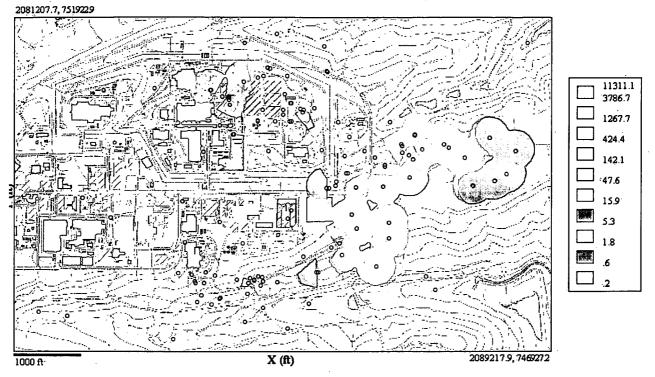


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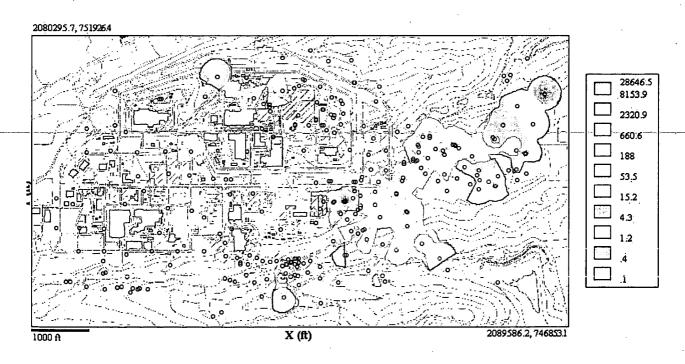


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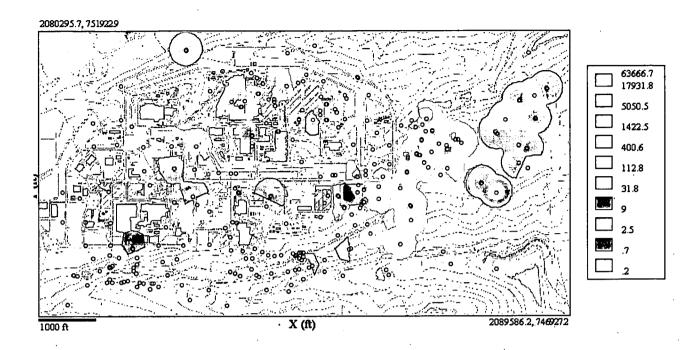


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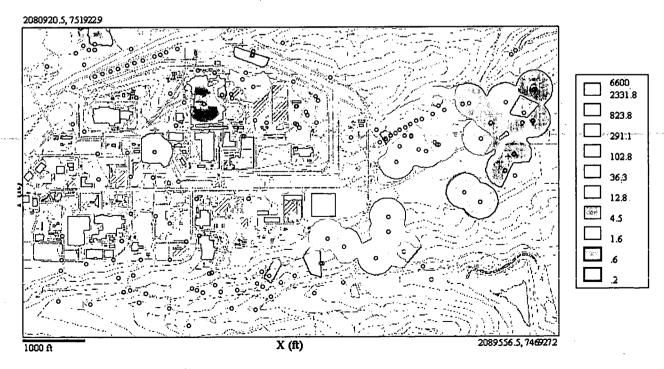


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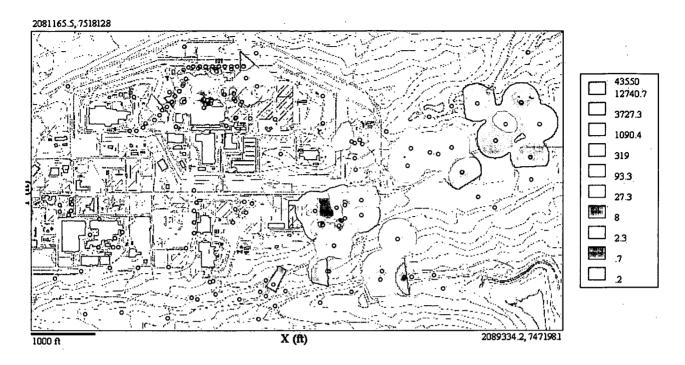


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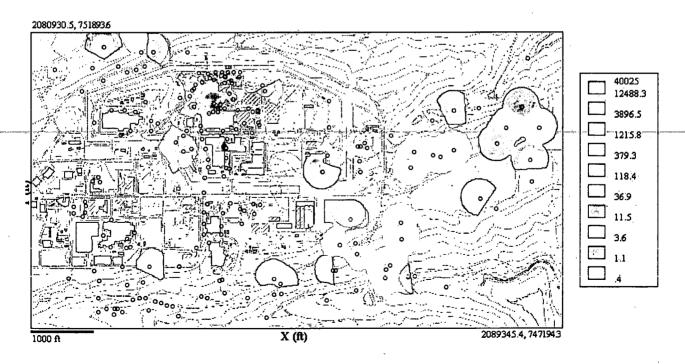


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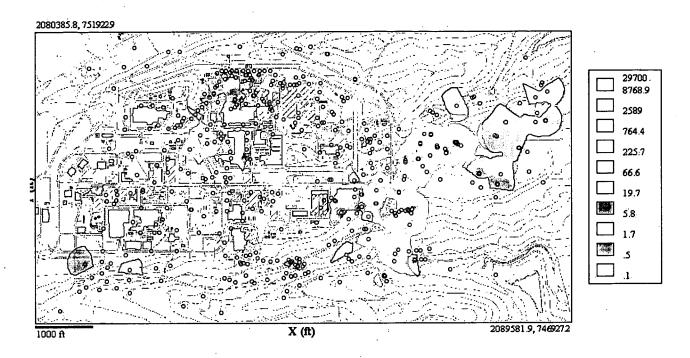


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## Isopleth Map of CARBON TETRACHLORIDE ug/L During 2000-2001

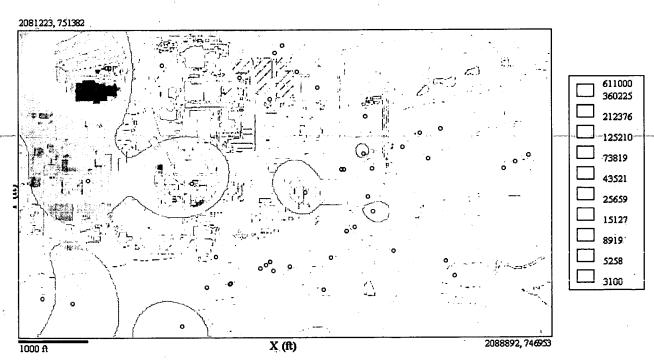


# Isopleth Map of CARBON TETRACHLORIDE ug/L During 2002-2003

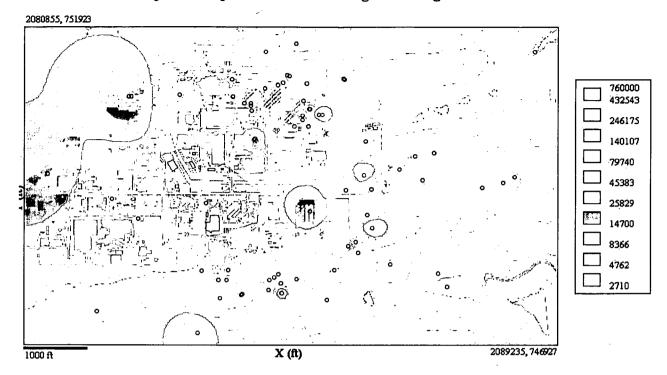


ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

## Isopleth Map of CHLORIDE ug/L During 1986-1987

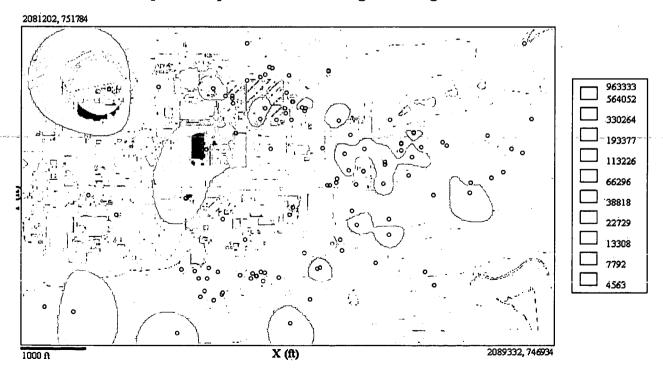


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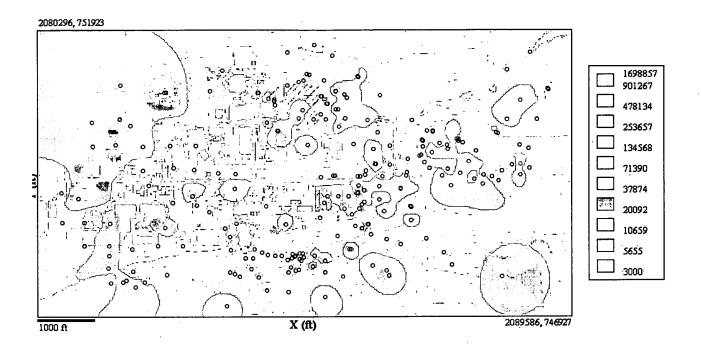


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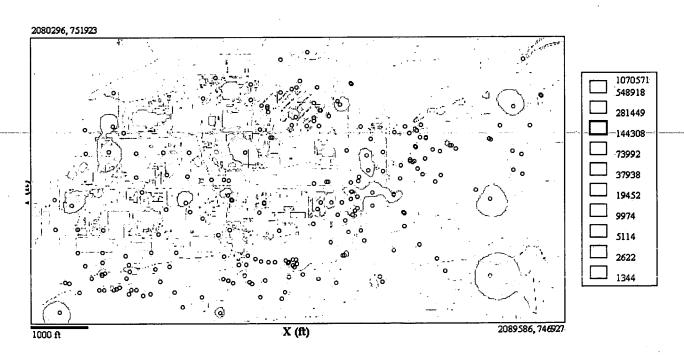


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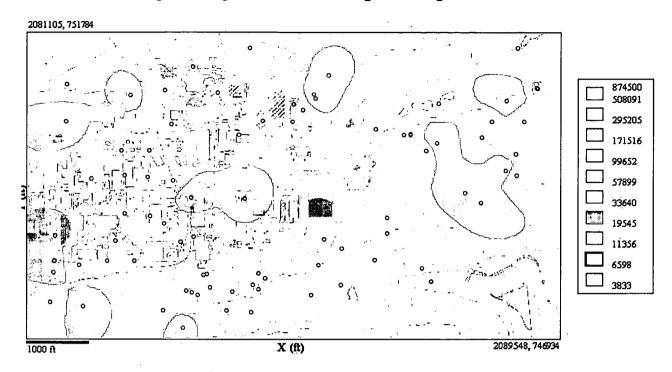


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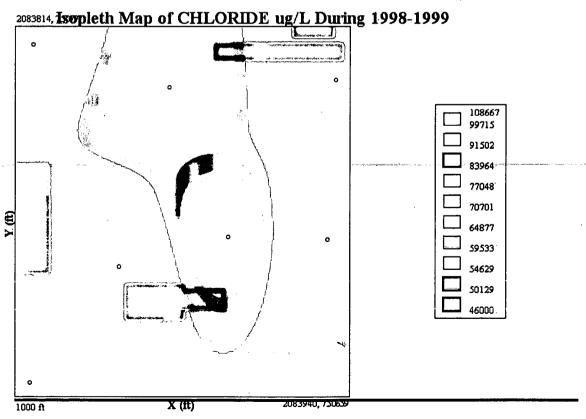
#### Isopleth Map of CHLORIDE ug/L During 1994-1995



#### Isopleth Map of CHLORIDE ug/L During 1996-1997

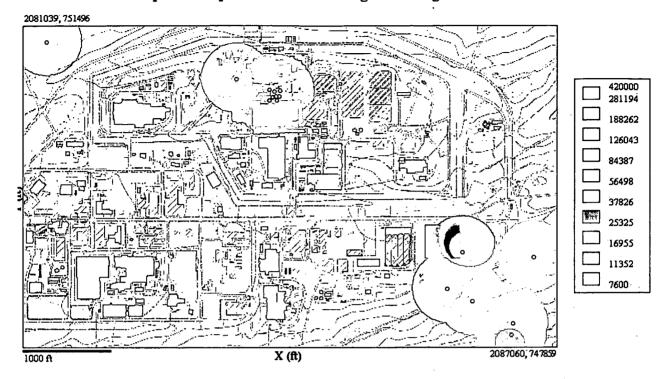


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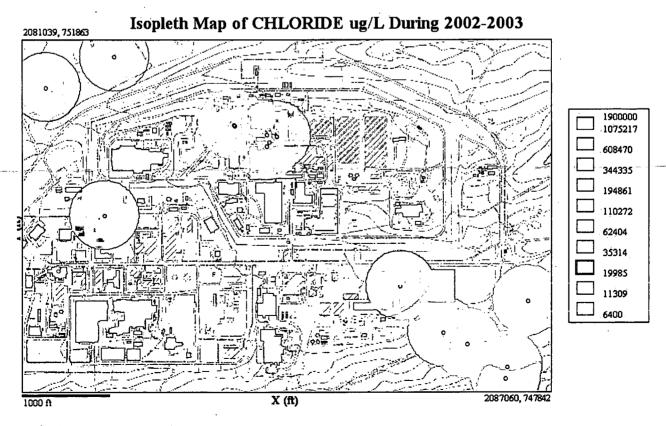


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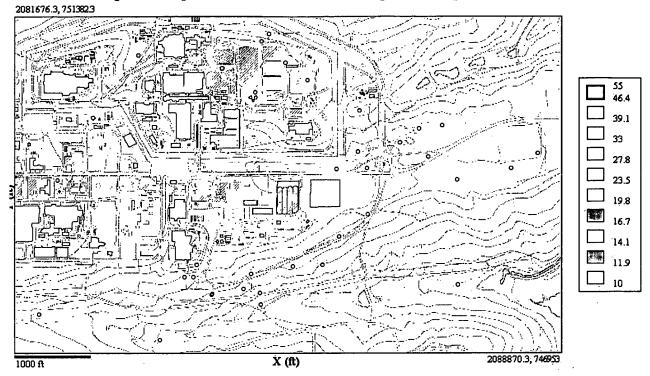


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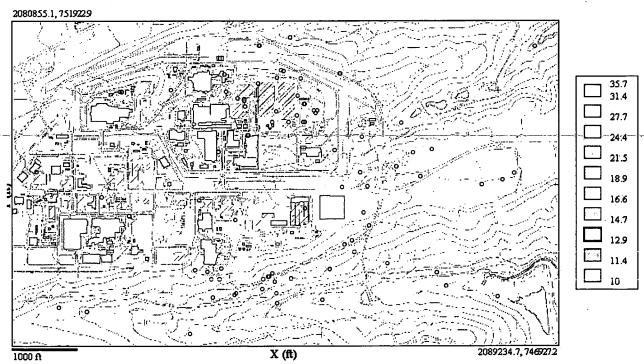
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## Isopleth Map of CHLOROETHANE ug/L During 1986-1987

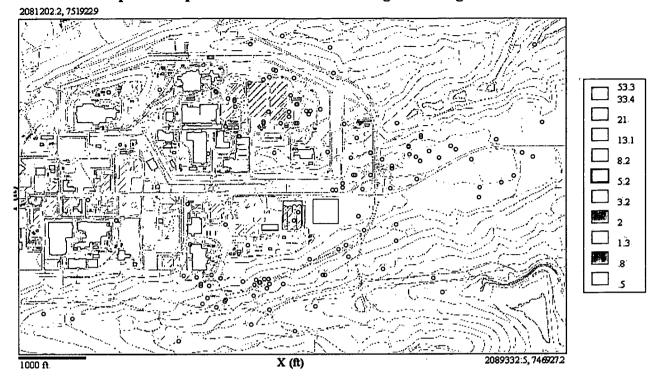


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#### Isopleth Map of CHLOROETHANE ug/L During 1988-1989

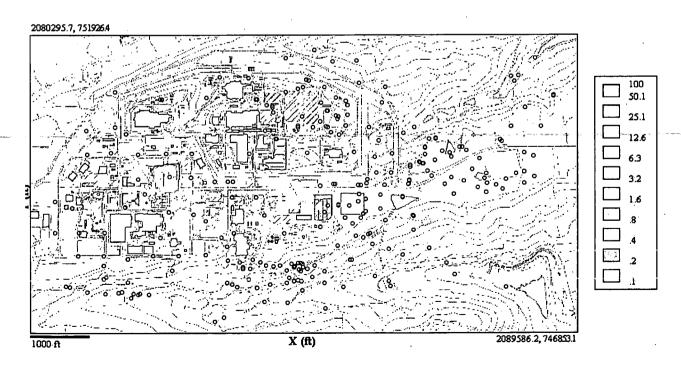


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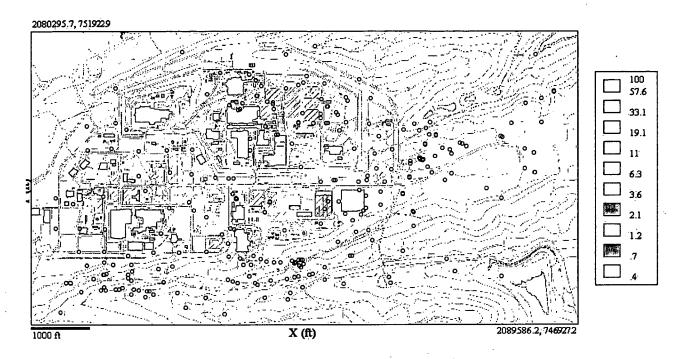


b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

# Isopleth Map of CHLOROETHANE ug/L During 1992-1993

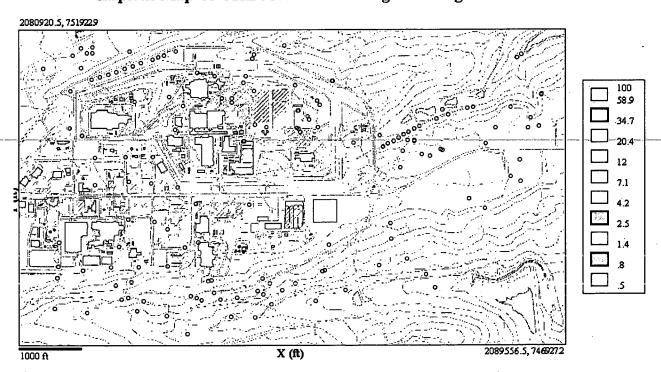


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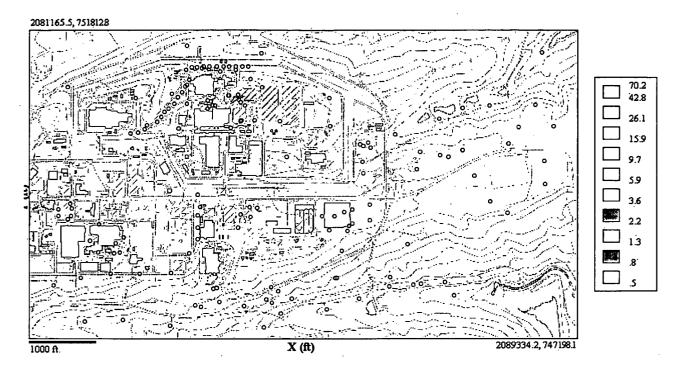


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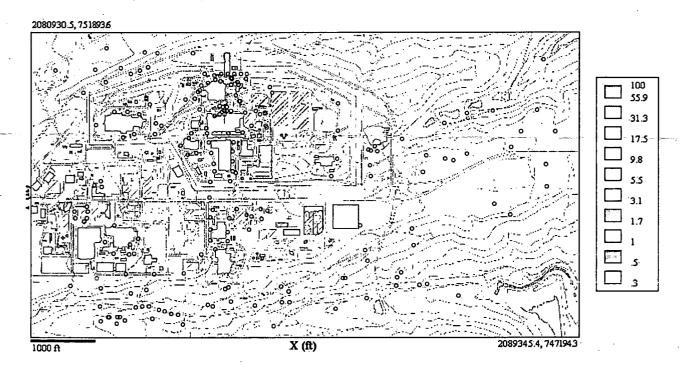


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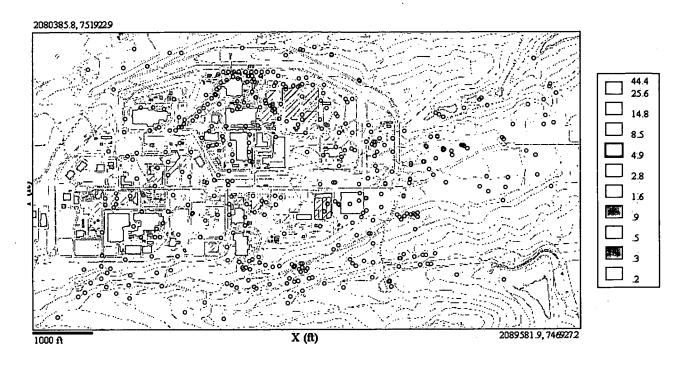


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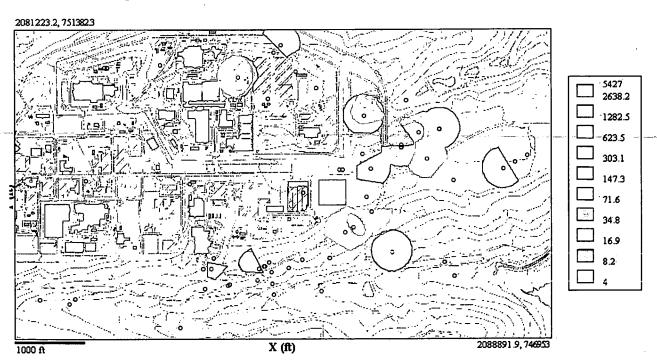


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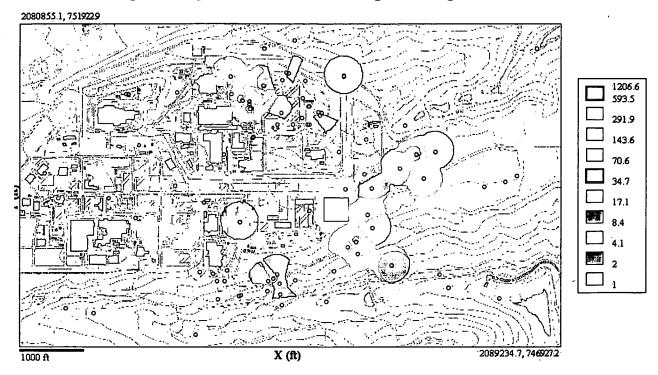


-ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

#### Isopleth Map of CHLOROFORM ug/L During 1986-1987

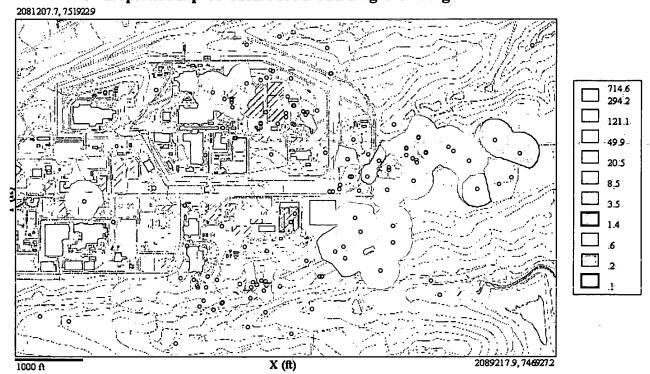


#### Isopleth Map of CHLOROFORM ug/L During 1988-1989

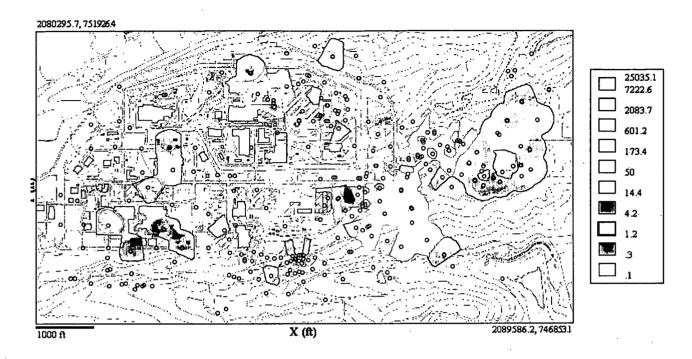


b All Set2 Sitewide 1988-1989 in Biodegradation.mdb

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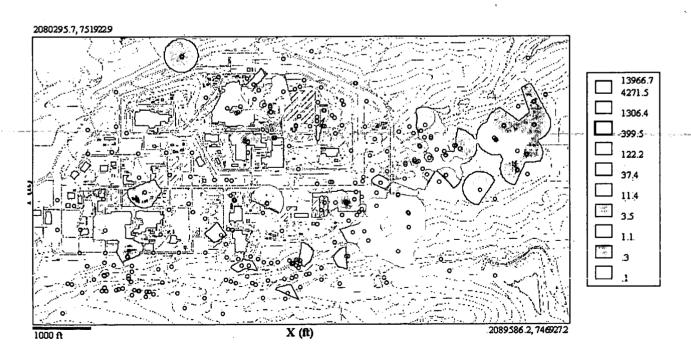


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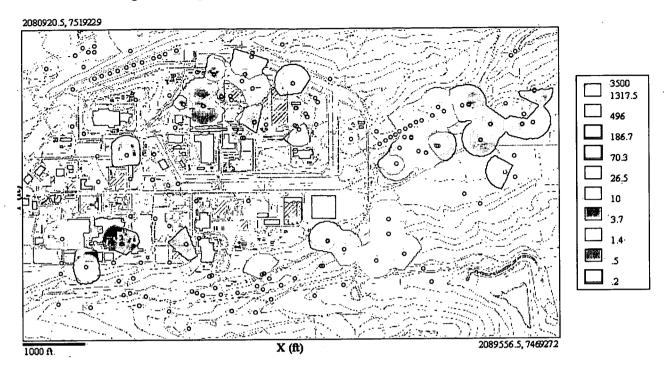


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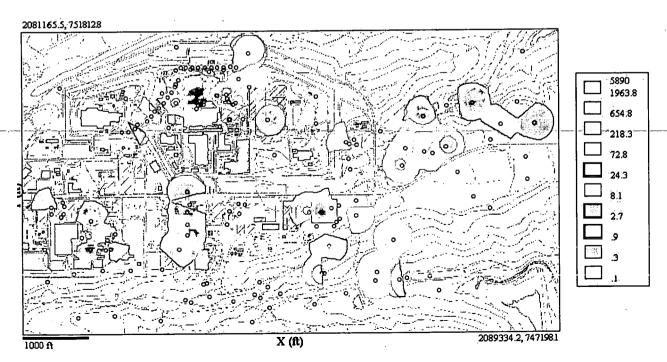


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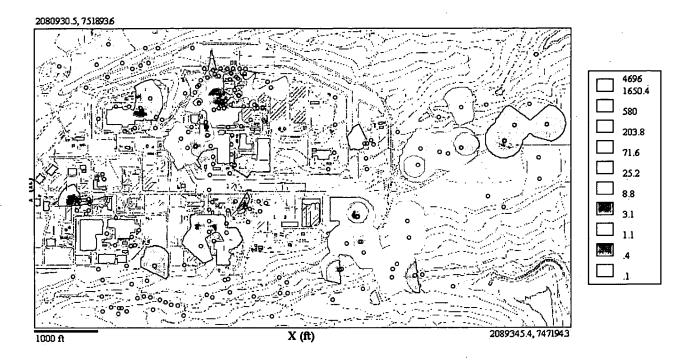


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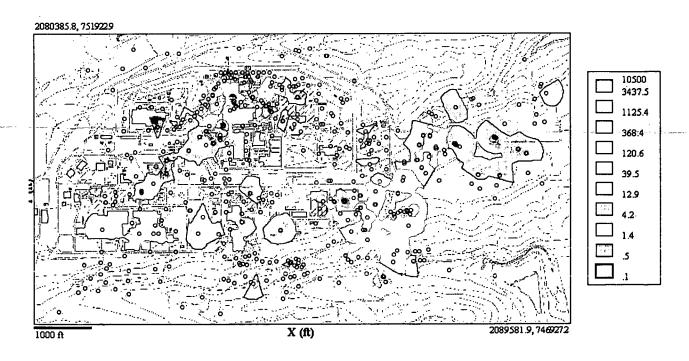


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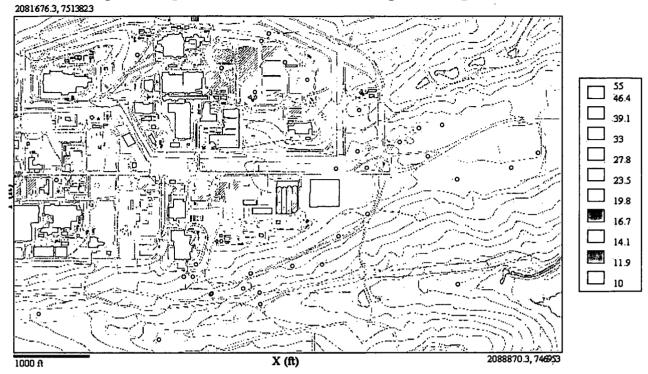


b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

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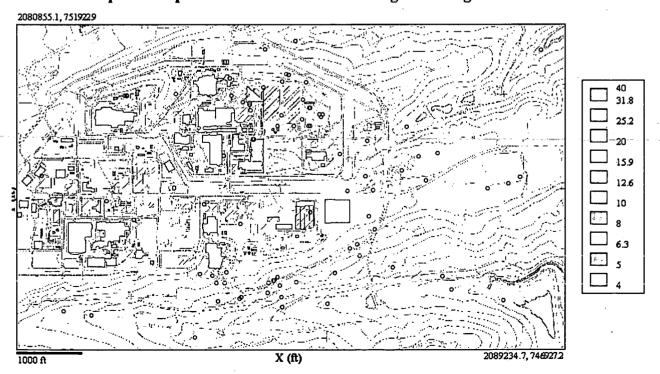


#### Isopleth Map of CHLOROMETHANE ug/L During 1986-1987

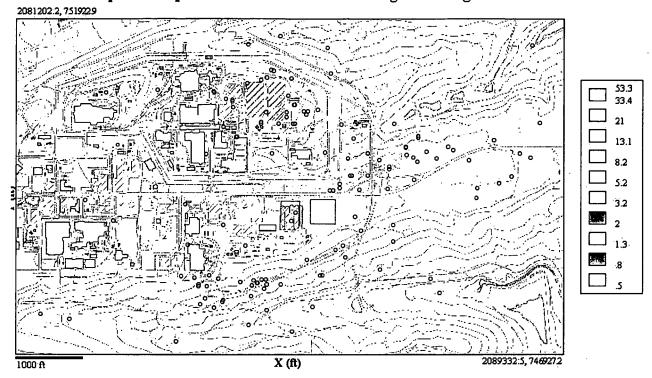


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

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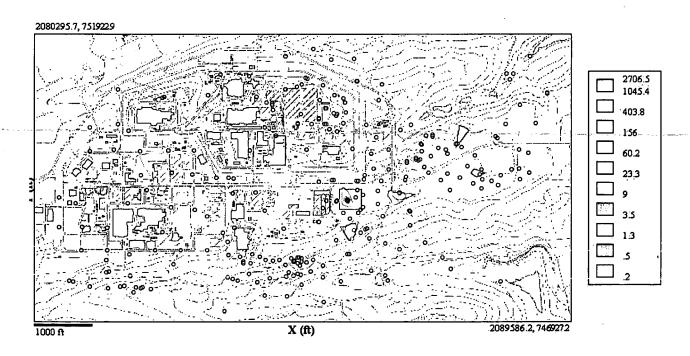


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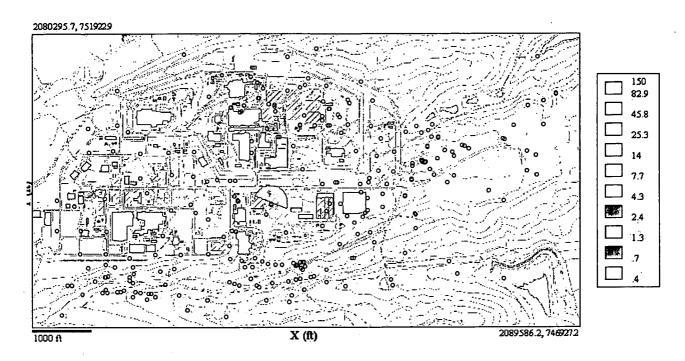


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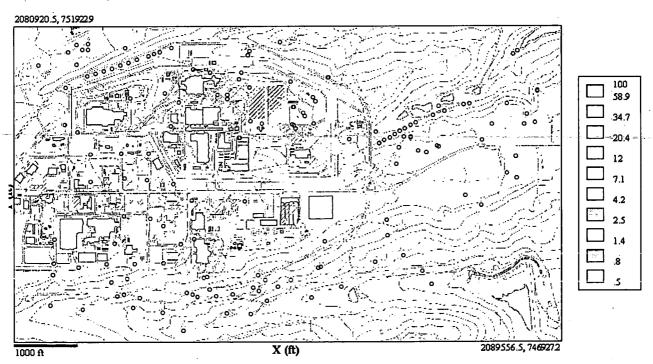


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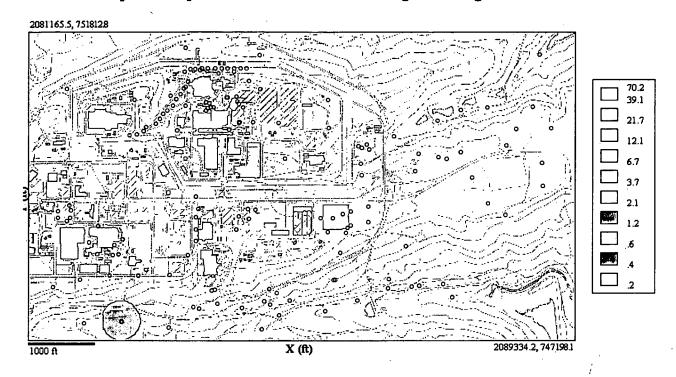


b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

## Isopleth Map of CHLOROMETHANE ug/L During 1996-1997

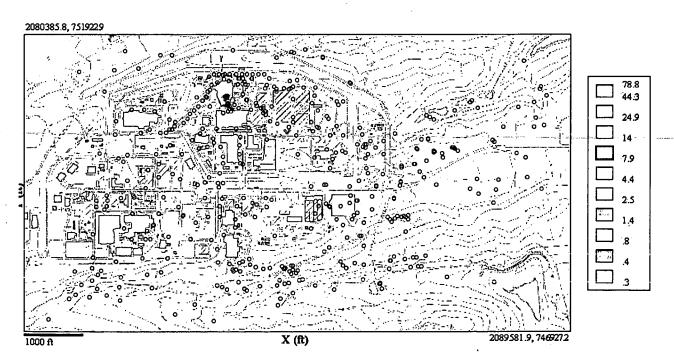


## Isopleth Map of CHLOROMETHANE ug/L During 1998-1999

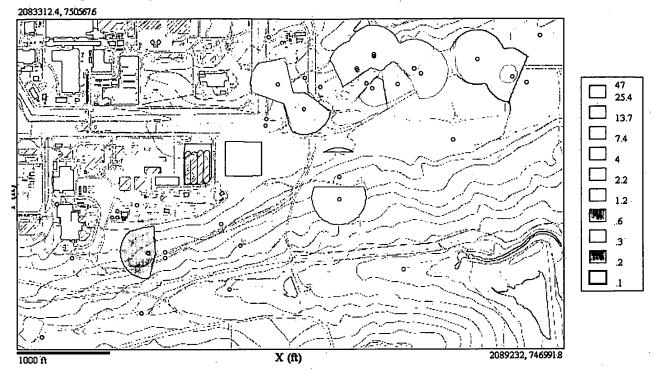


b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

## Isopleth Map of CHLOROMETHANE ug/L During 2002-2003

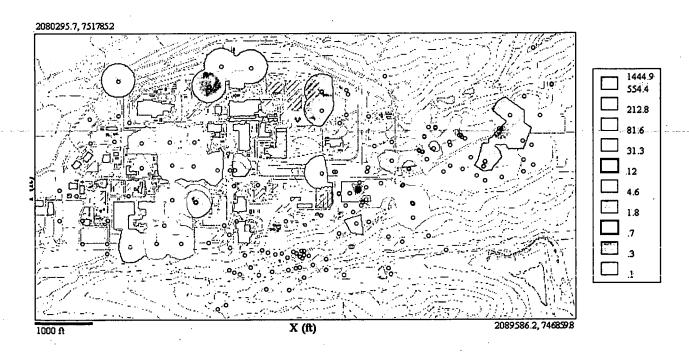


Isopleth Map of cis-1,2-DICHLOROETHENE ug/L During 1990-1991

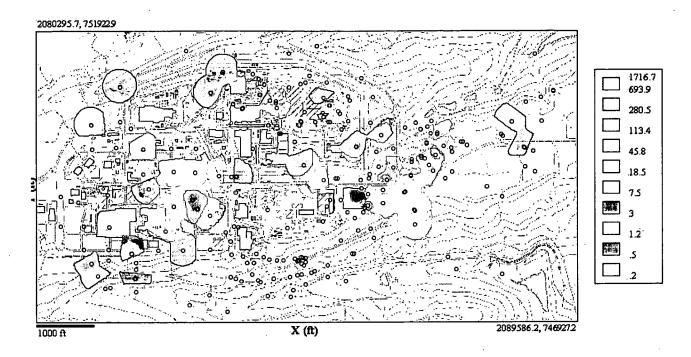


b All Set2 Sitewide 1990-1991 in Biodegradation mdb

Isopleth Map of cis-1,2-DICHLOROETHENE ug/L During 1992-1993

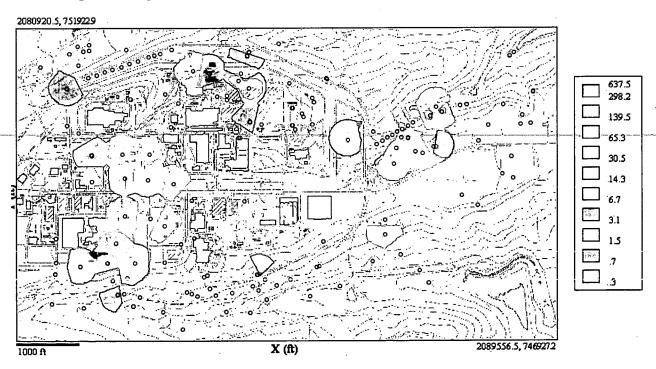


# Isopleth Map of cis-1,2-DICHLOROETHENE ug/L During 1994-1995

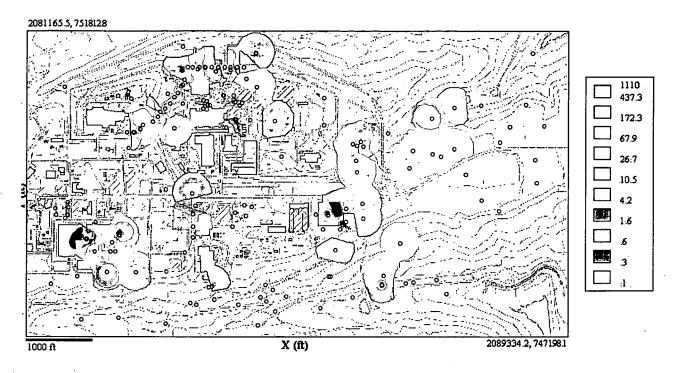


b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

## Isopleth Map of cis-1,2-DICHLOROETHENE ug/L During 1996-1997

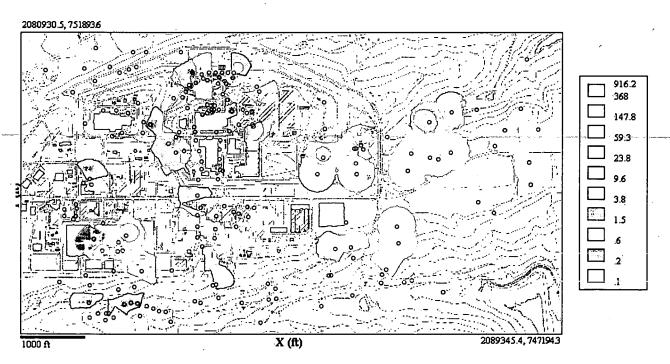


# Isopleth Map of cis-1,2-DICHLOROETHENE ug/L During 1998-1999

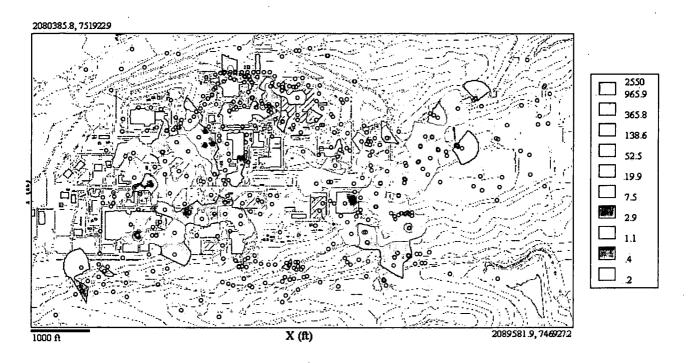


b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

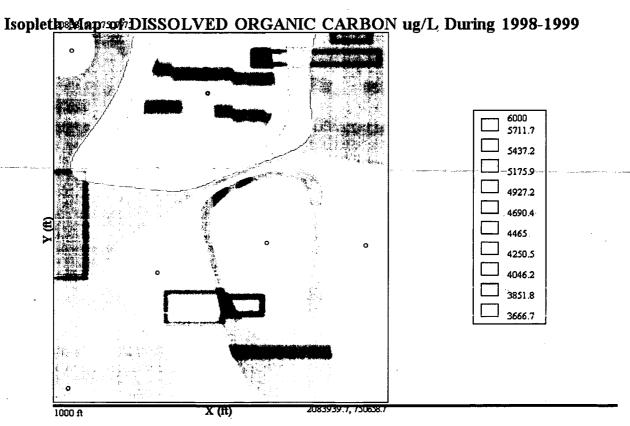
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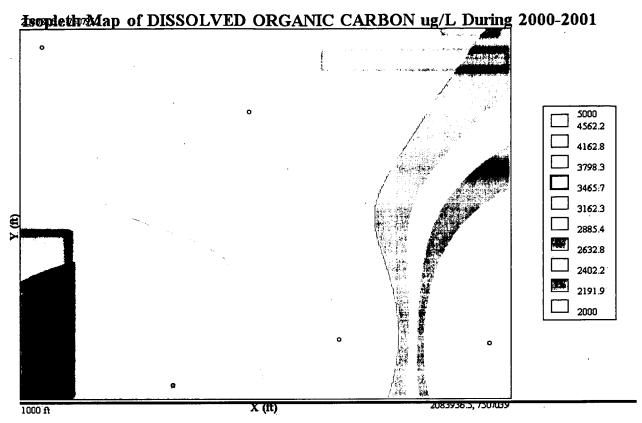


## Isopleth Map of cis-1,2-DICHLOROETHENE ug/L During 2002-2003

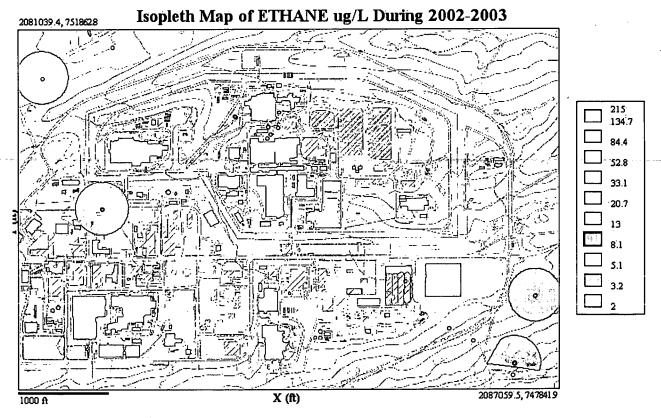


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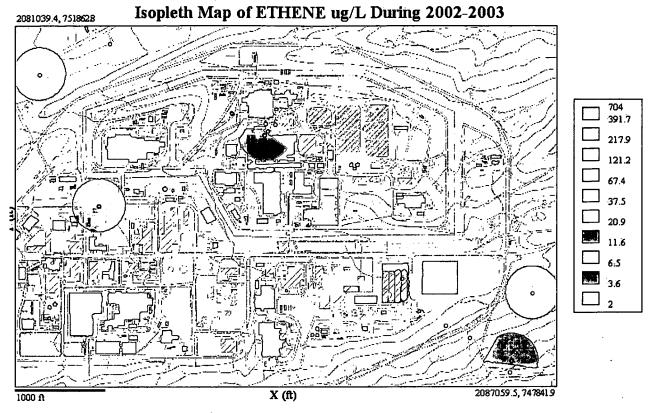




b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

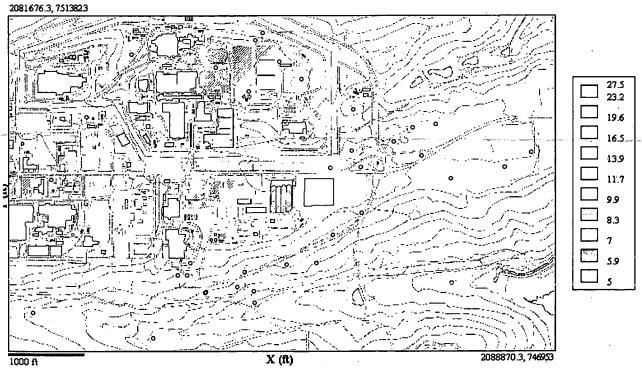


-ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

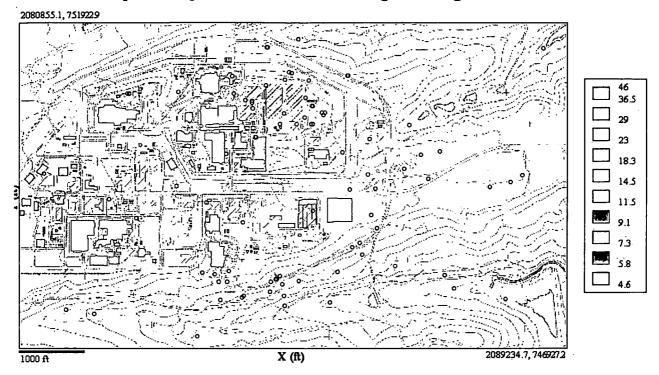


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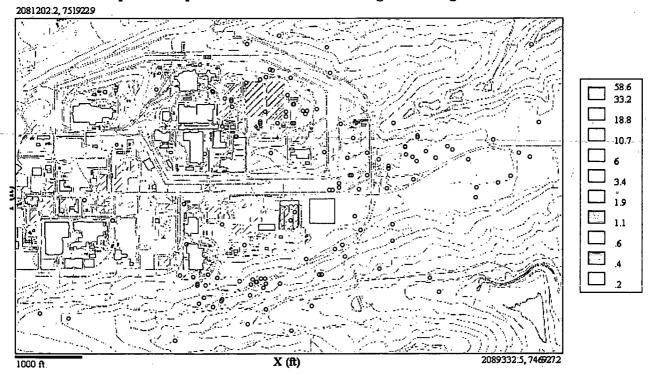


## Isopleth Map of ETHYLBENZENE ug/L During 1988-1989

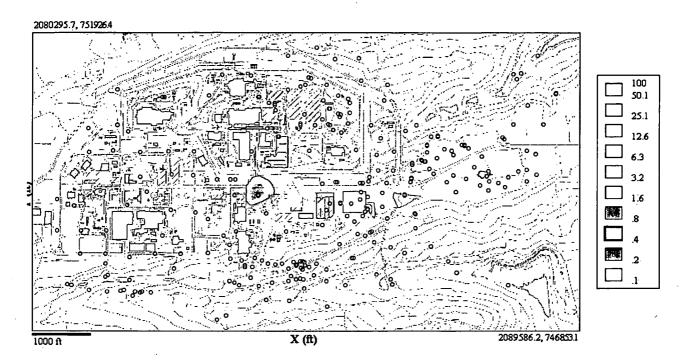


b All Set2 Sitewide 1988-1989 in Biodegradation.mdb

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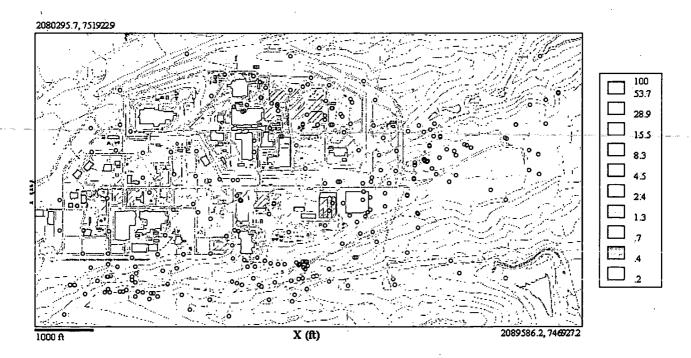


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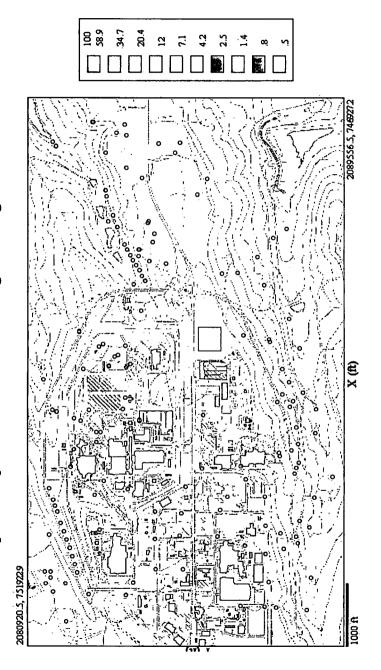


b All Set2 Sitewide 1992-1993 in Biodegradation.mdb

#### Isopleth Map of ETHYLBENZENE ug/L During 1994-1995

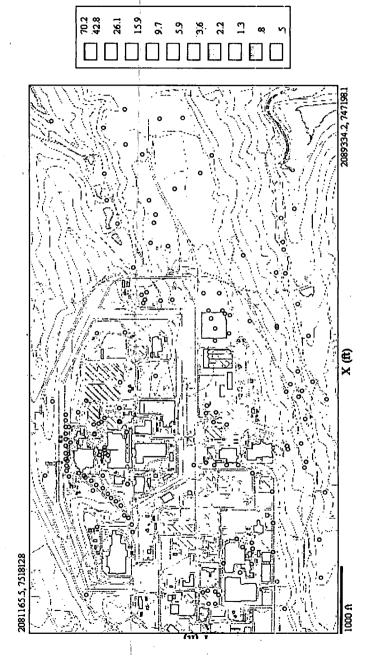


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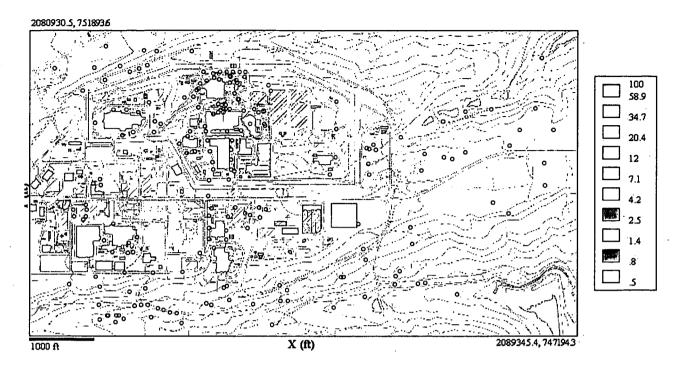


b All Set2 Sitewide 1996-1997 in Biodegradation mdb

Isopleth Map of ETHYLBENZENE ug/L During 1998-1999

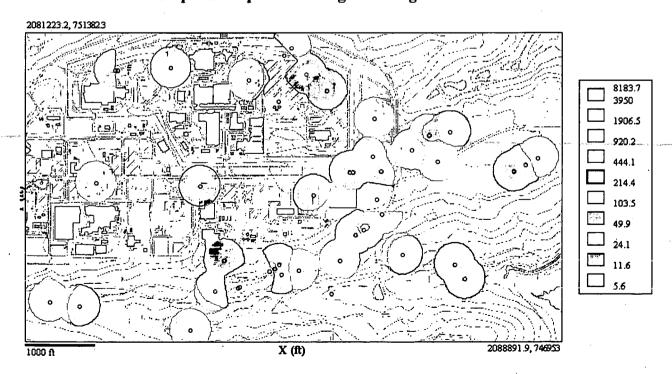


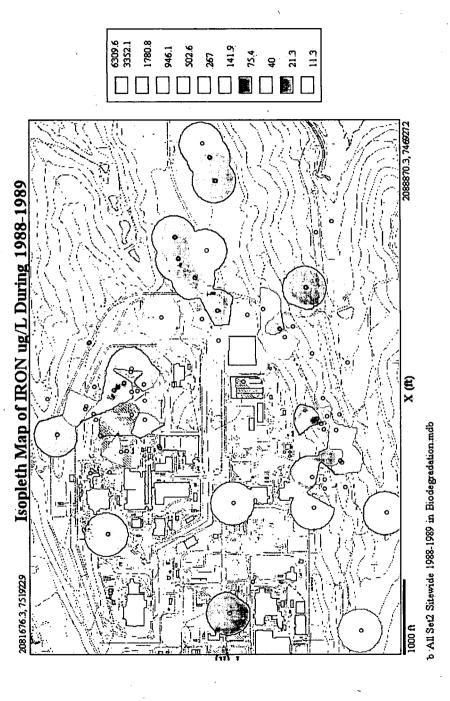
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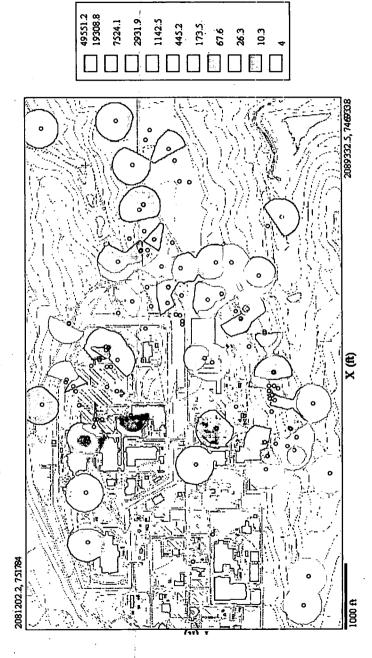
b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

# Isopleth Map of IRON ug/L During 1986-1987

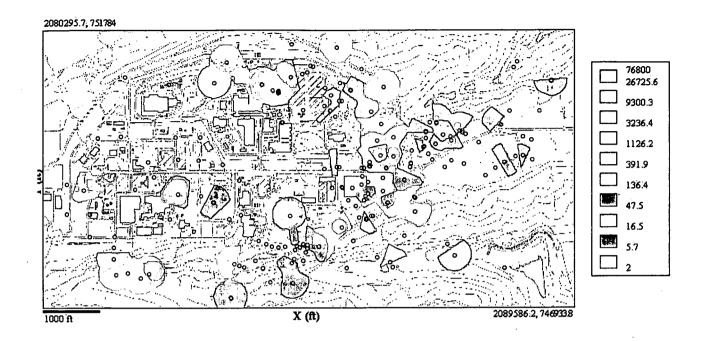




Isopleth Map of RON ug/L During 1990-1991

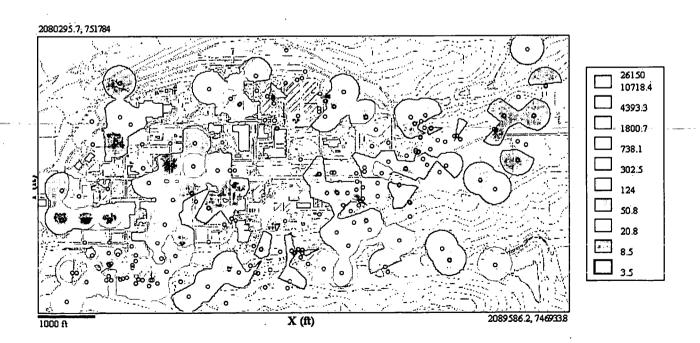


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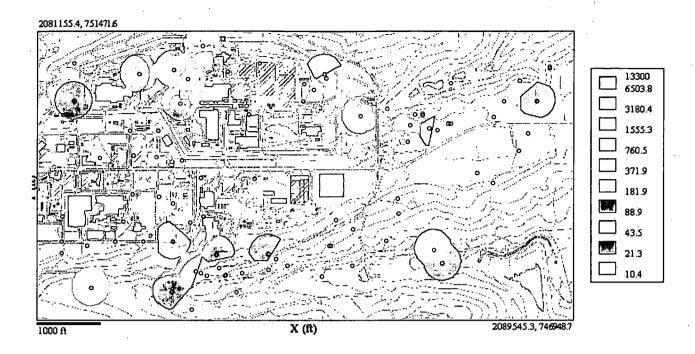


b All Set2 Sitewide 1992-1993 in Biodegradation.mdb

# Isopleth Map of IRON ug/L During 1994-1995

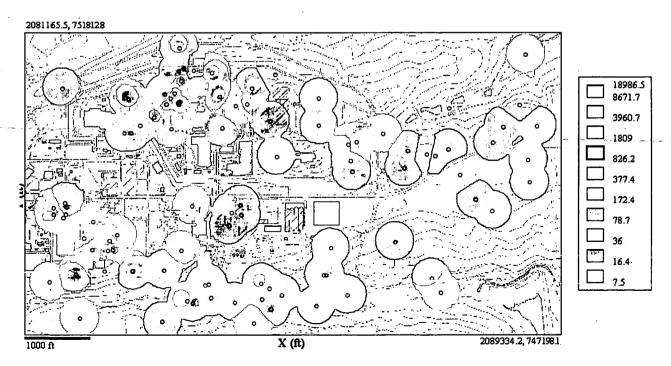


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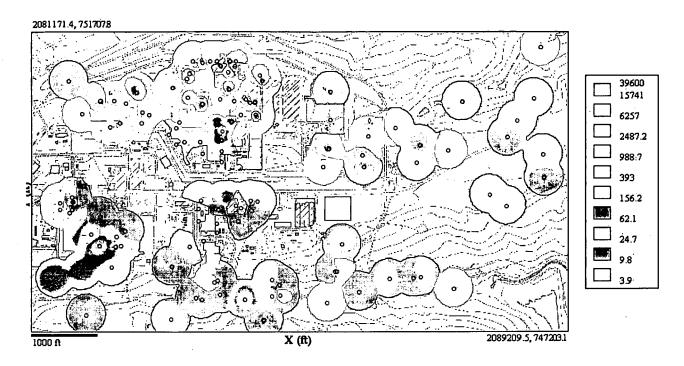


b All Set2 Sitewide 1996-1997 in Biodegradation.mdb

## Isopleth Map of IRON ug/L During 1998-1999

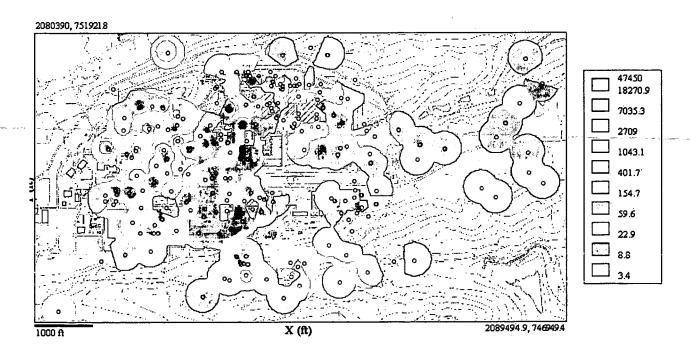


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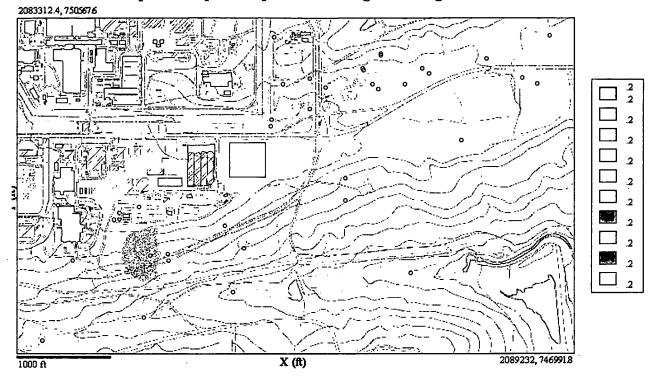


b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

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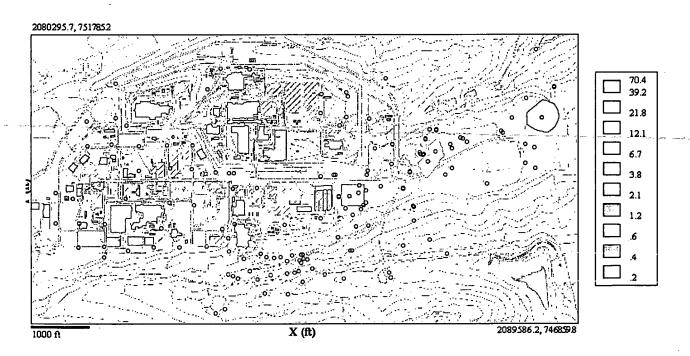


#### Isopleth Map of m+p XYLENE ug/L During 1990-1991

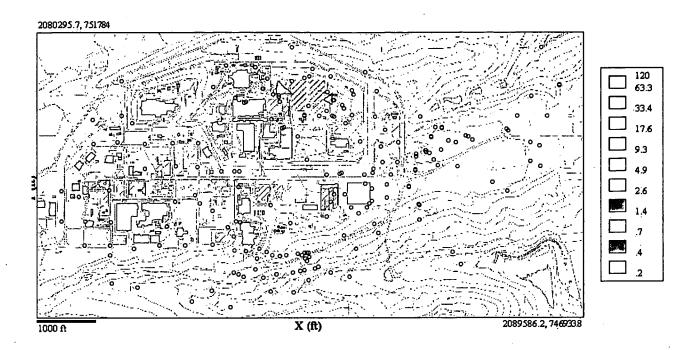


b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

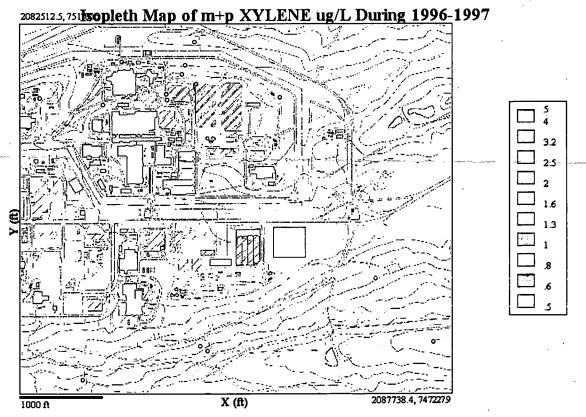
## Isopleth Map of m+p XYLENE ug/L During 1992-1993



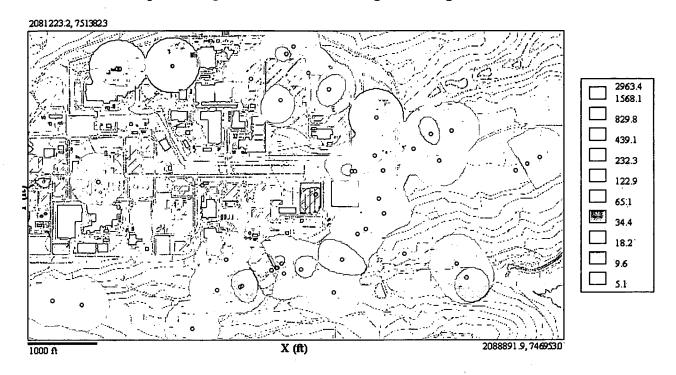
#### Isopleth Map of m+p XYLENE ug/L During 1994-1995



b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

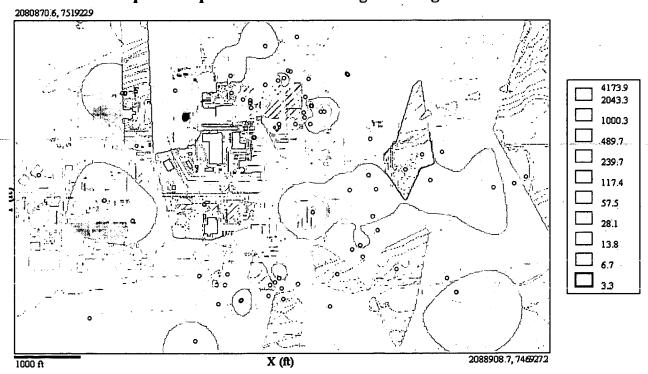


#### Isopleth Map of MANGANESE ug/L During 1986-1987

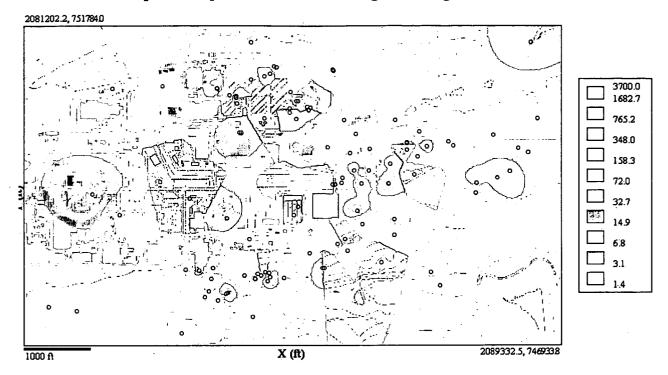


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

## Isopleth Map of MANGANESE ug/L During 1988-1989

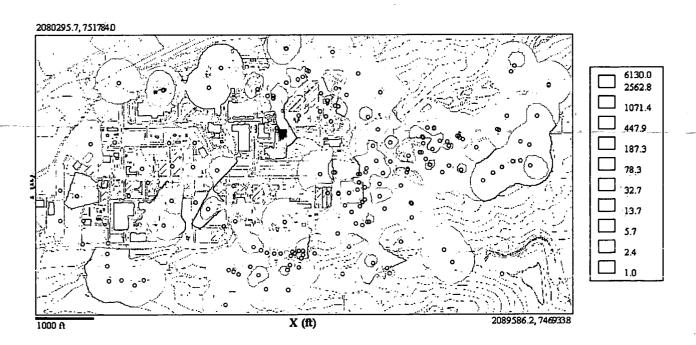


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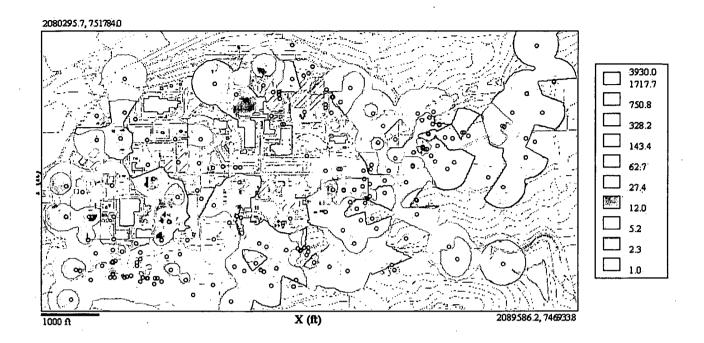
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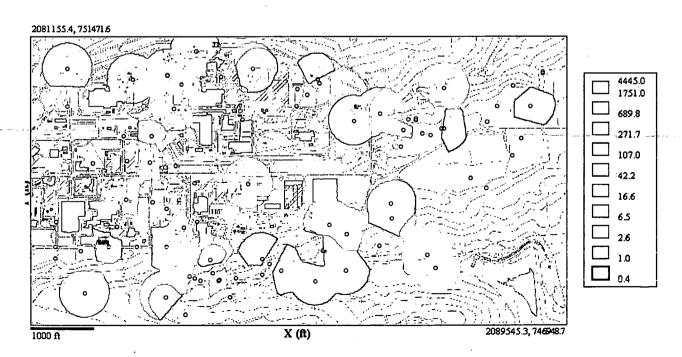
467

#### Isopleth Map of MANGANESE ug/L During 1994-1995

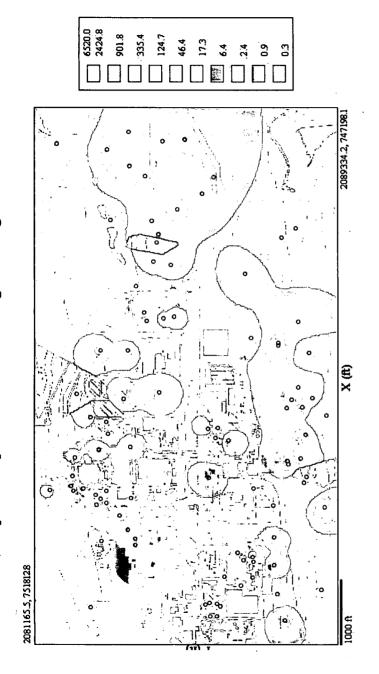


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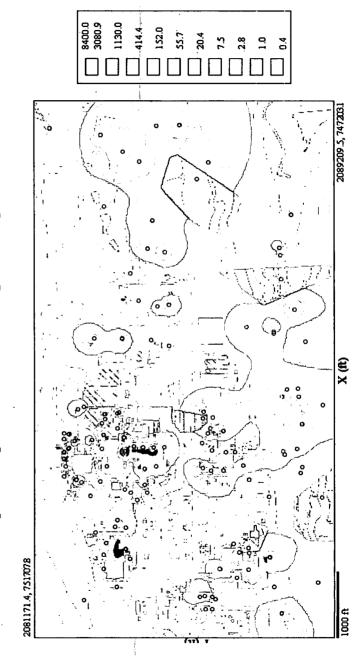


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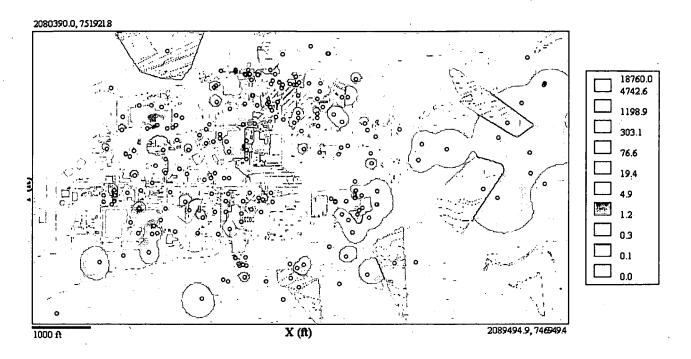
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# Isopleth Map of MANGANESE ug/L During 2000-2001



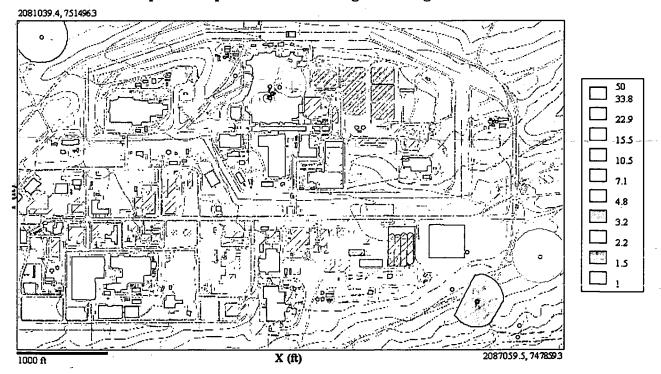
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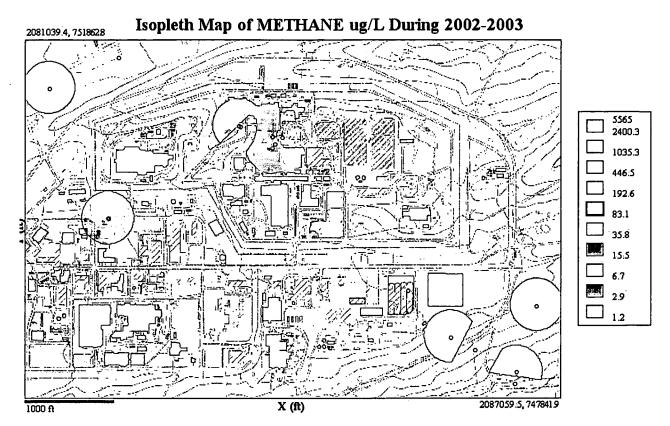
# Isopleth Map of MANGANESE ug/L During 2002-2003



b All Set2 Sitewide 2002-2003 in Biodegradation mdb

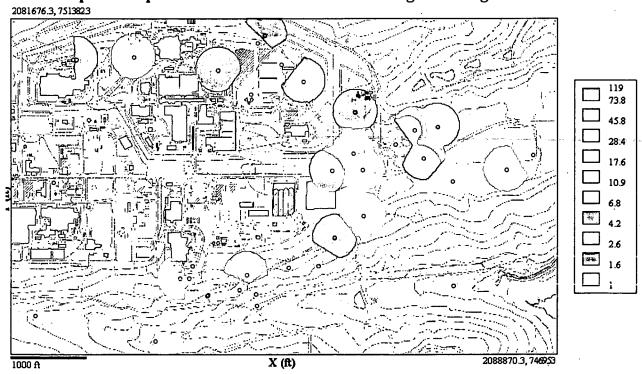
#### Isopleth Map of METHANE ug/L During 2000-2001





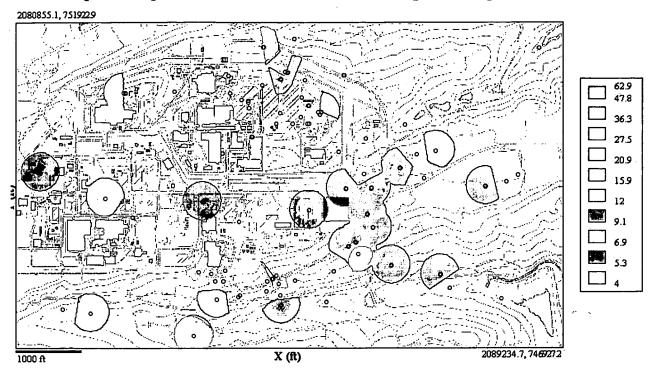
-ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb





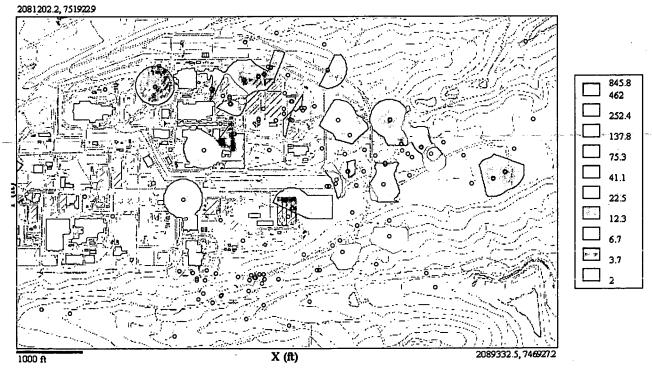
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#### Isopleth Map of METHYLENE CHLORIDE ug/L During 1988-1989

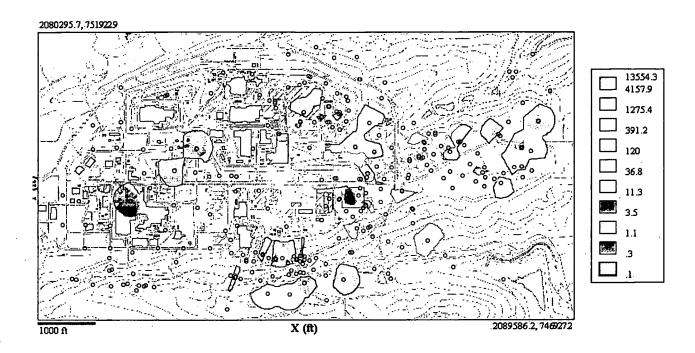


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## Isopleth Map of METHYLENE CHLORIDE ug/L During 1990-1991

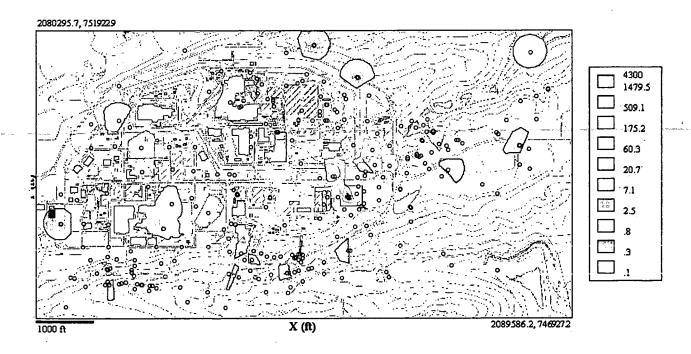


# Isopleth Map of METHYLENE CHLORIDE ug/L During 1992-1993

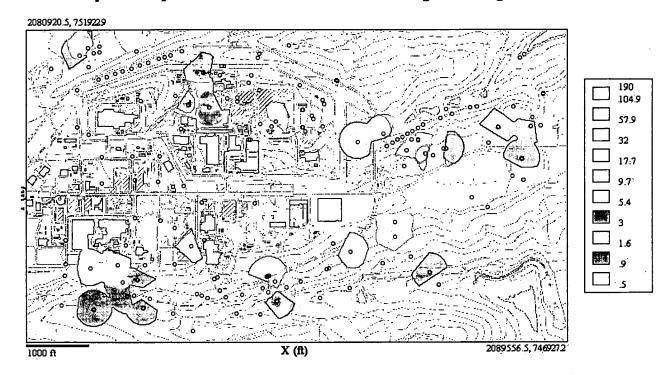


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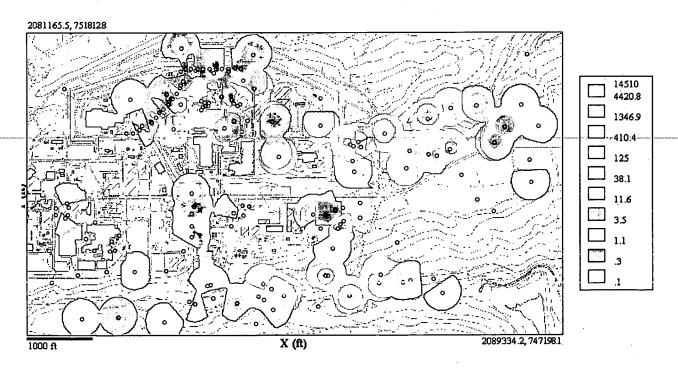


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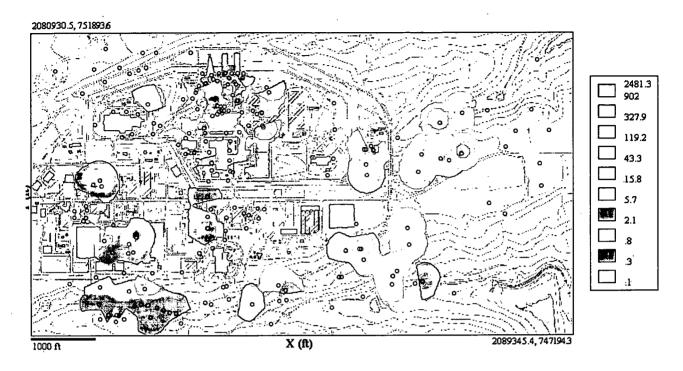


b All Set2 Sitewide 1996-1997 in Biodegradation.mdb

# Isopleth Map of METHYLENE CHLORIDE ug/L During 1998-1999

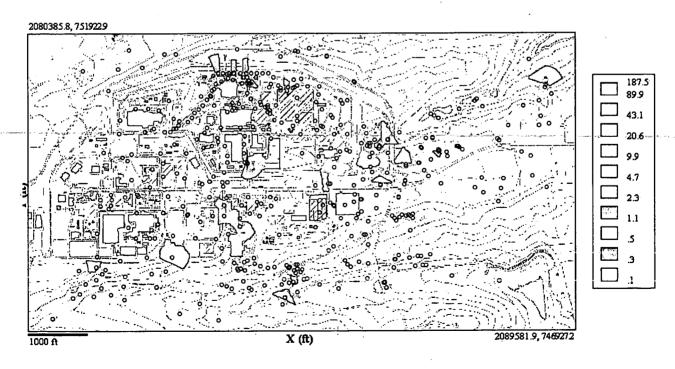


## Isopleth Map of METHYLENE CHLORIDE ug/L During 2000-2001

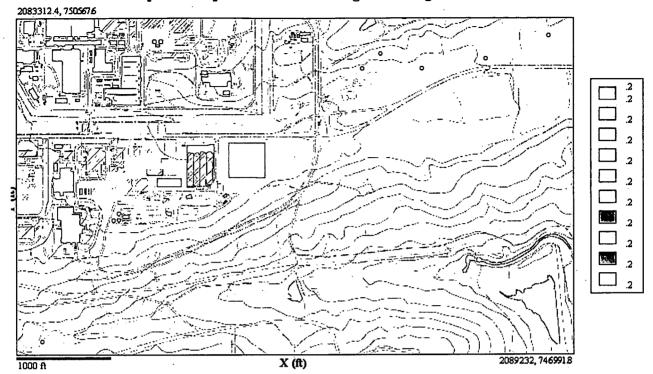


b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

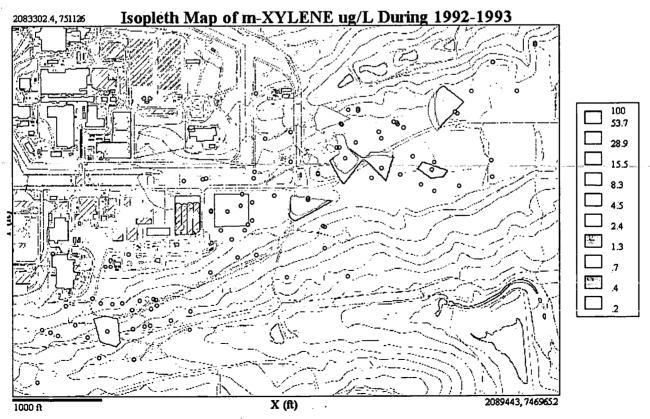
# Isopleth Map of METHYLENE CHLORIDE ug/L During 2002-2003



## Isopleth Map of m-XYLENE ug/L During 1990-1991

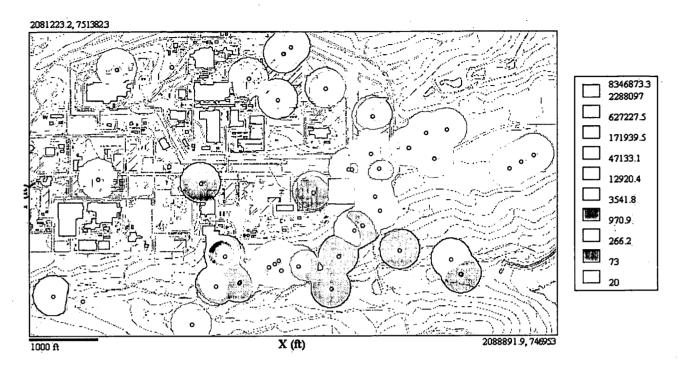


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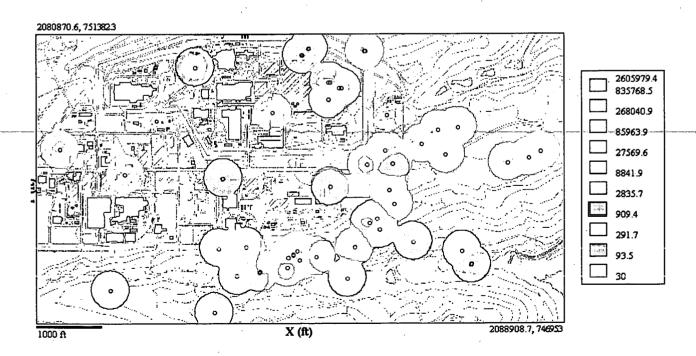
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## Isopleth Map of NITRATE ug/L During 1986-1987

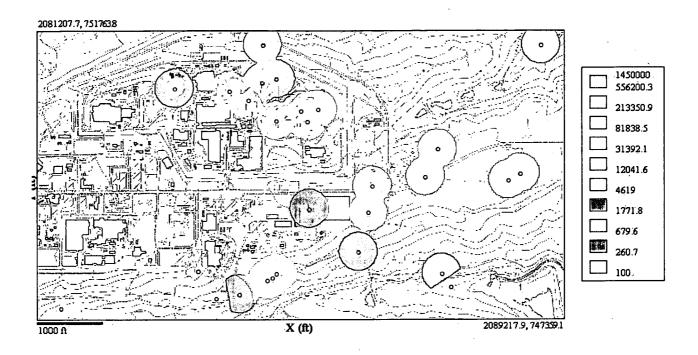


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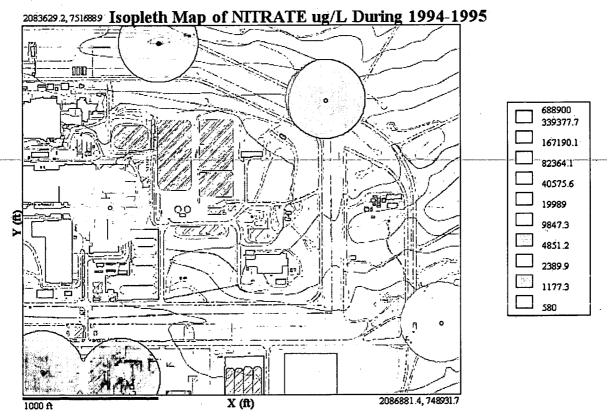
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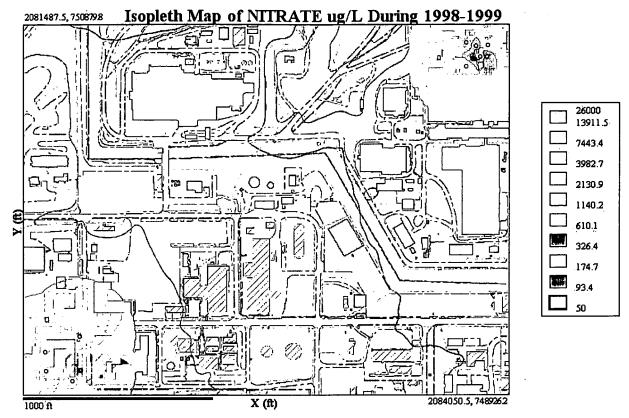
## Isopleth Map of NITRATE ug/L During 1990-1991



b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

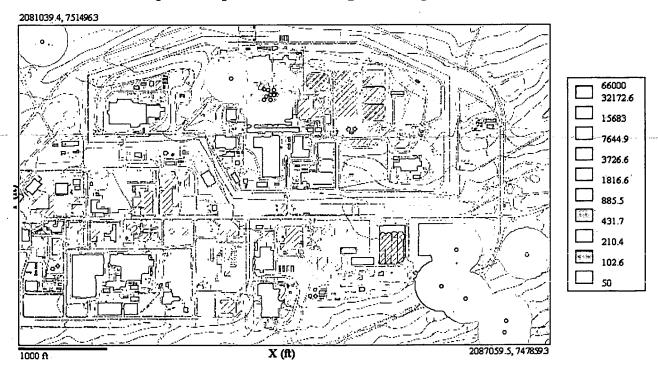


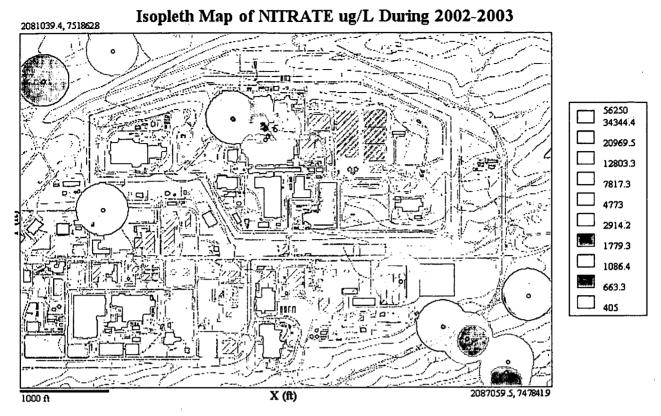
b All Set2 Sitewide 1994-1995 in Biodegradation.mdb



b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

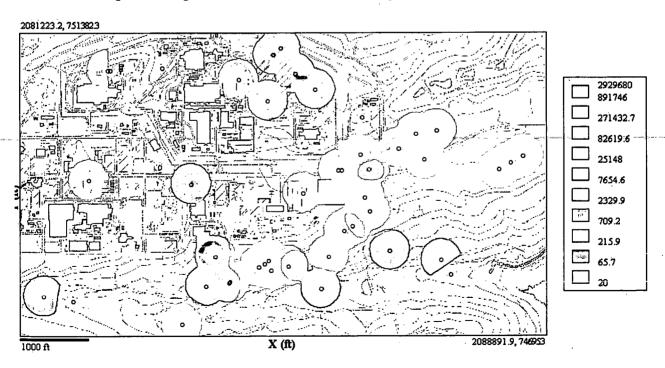
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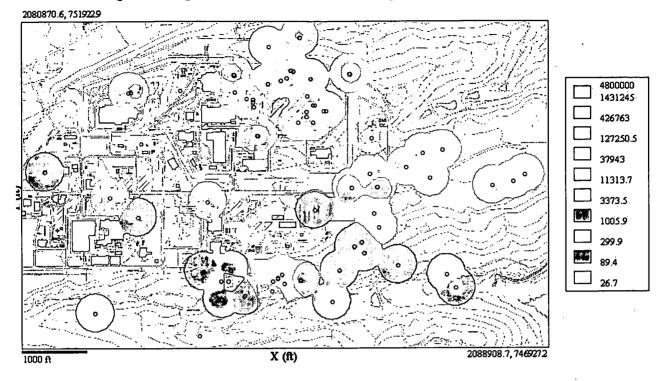
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## Isopleth Map of NITRATE/NITRITE ug/L During 1986-1987



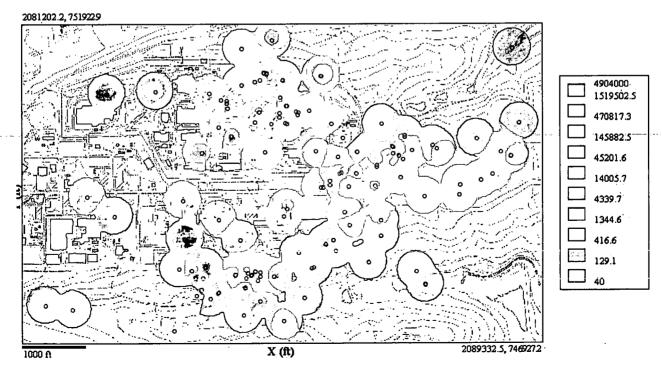
b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

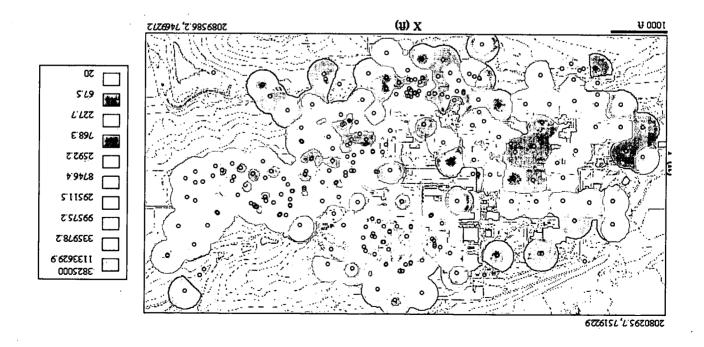
## Isopleth Map of NITRATE/NITRITE ug/L During 1988-1989



b All Set2 Sitewide 1988-1989 in Biodegradation.mdb

# Isopleth Map of NITRATE/NITRITE ug/L During 1990-1991

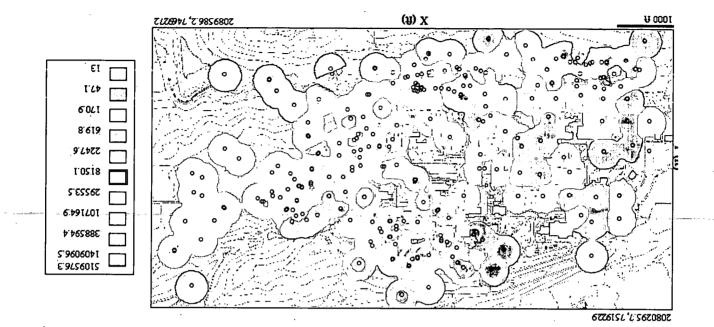




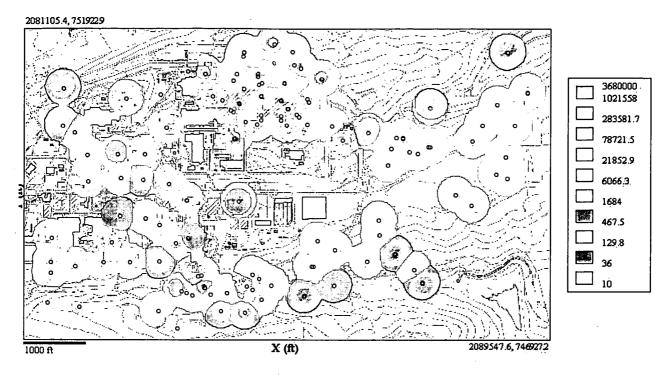
Isopleth Map of NITRATE/NITRITE ug/L During 1992-1993

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Isopleth Map of NITRATE/NITRITE ug/L During 1994-1995

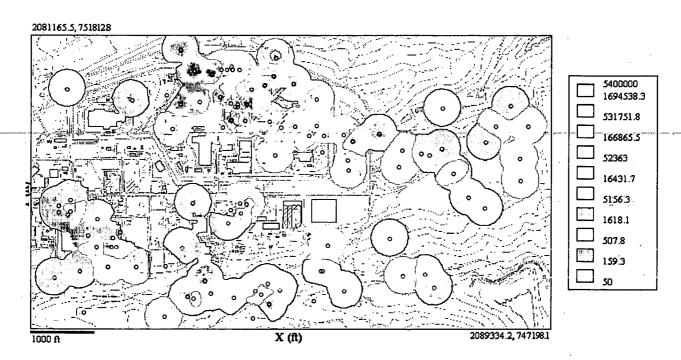


#### Isopleth Map of NTTRATE/NTTRITE ug/L During 1996-1997

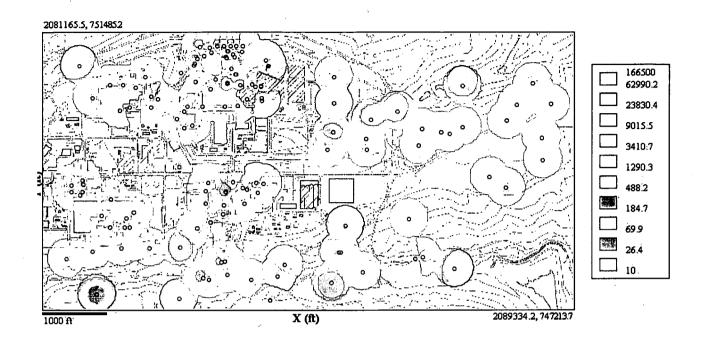


b All Set2 Sitewide 1996-1997 in Biodegradation.mdb

#### Isopleth Map of NITRATE/NITRITE ug/L During 1998-1999

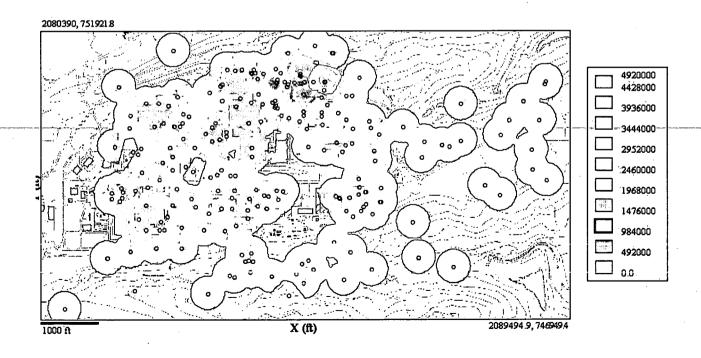


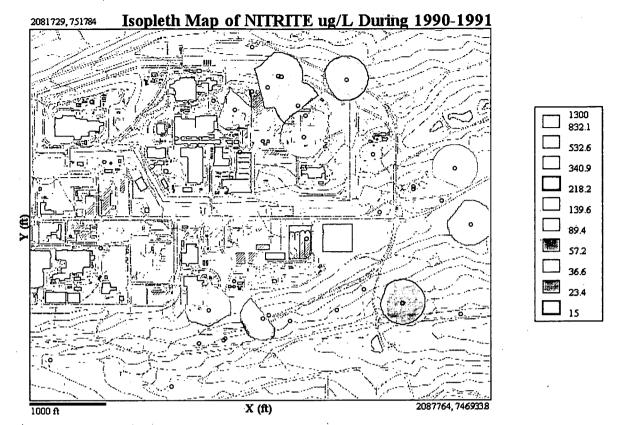
## Isopleth Map of NITRATE/NITRITE ug/L During 2000-2001



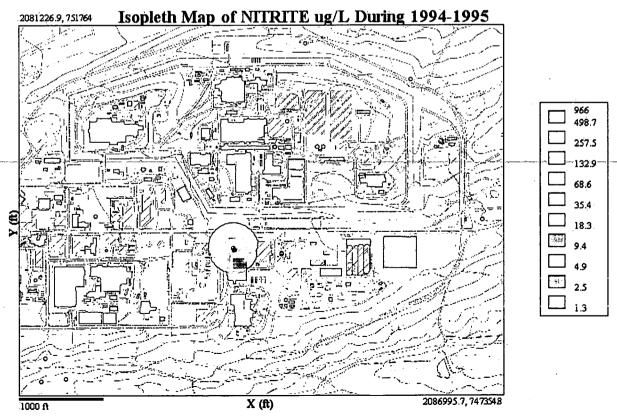
b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

## Isopleth Map of NITRATE/NITRITE ug/L During 2002-2003

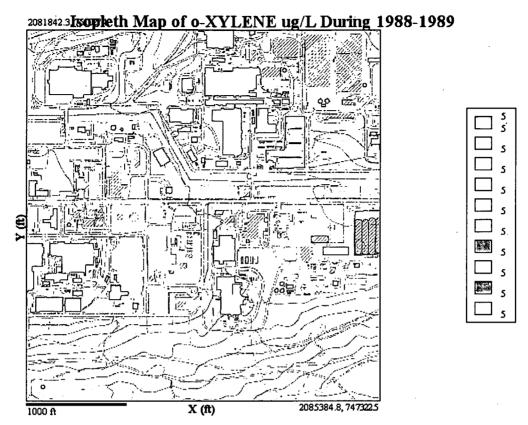




b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

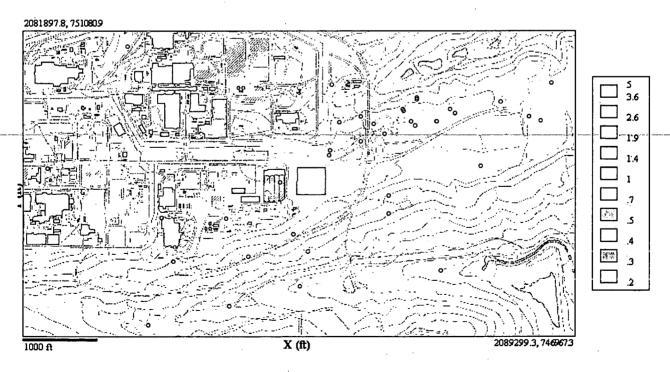


b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

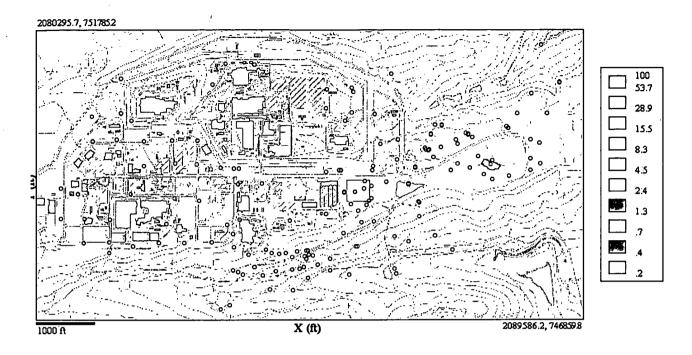


b All Set2 Sitewide 1988-1989 in Biodegradation.mdb

## Isopleth Map of o-XYLENE ug/L During 1990-1991

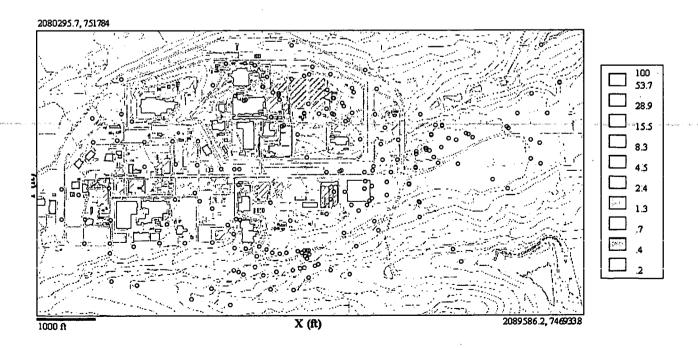


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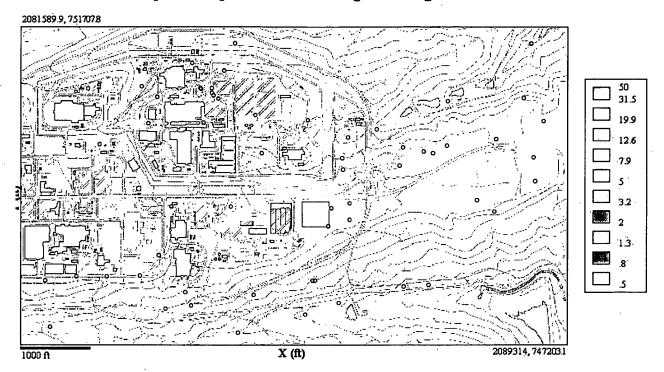


b All Set2 Sitewide 1992-1993 in Biodegradation mdb

#### Isopleth Map of o-XYLENE ug/L During 1994-1995

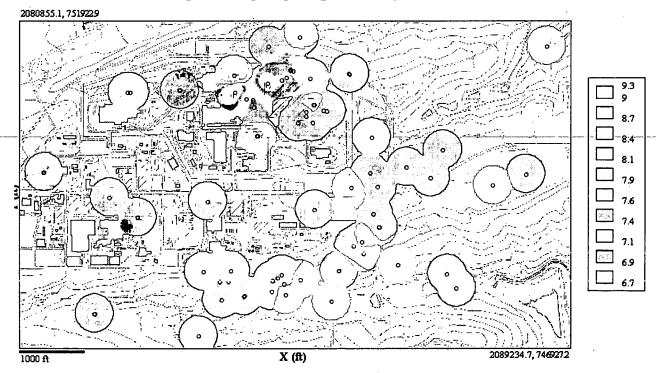


## Isopleth Map of o-XYLENE ug/L During 1998-1999

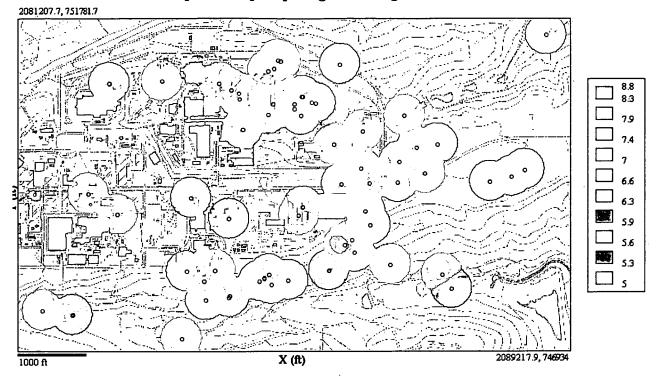


b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

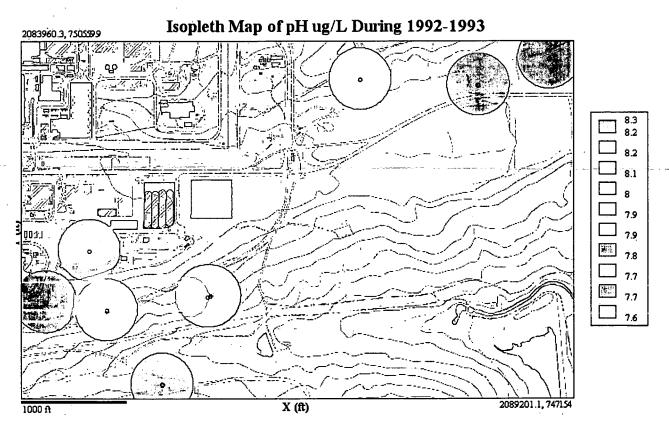
## Isopleth Map of pH ug/L During 1988-1989



# Isopleth Map of pH ug/L During 1990-1991

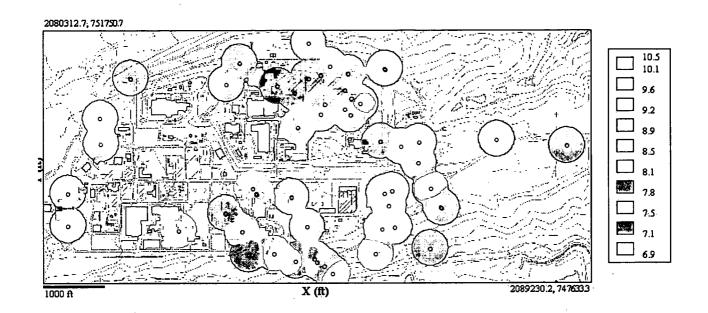


b All Set2 Sitewide 1990-1991 in Biodegradation.mdb

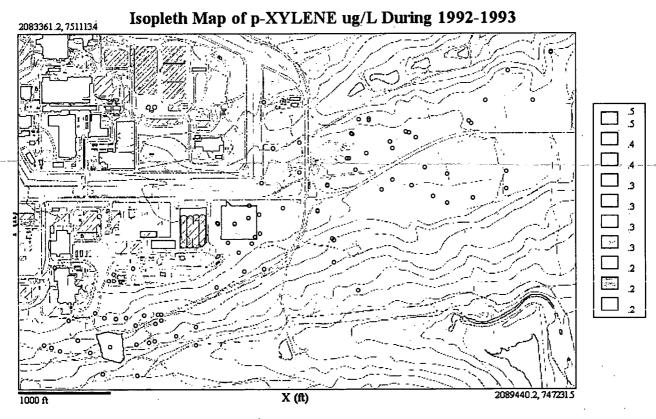


b All Set2 Sitewide 1992-1993 in Biodegradation.mdb

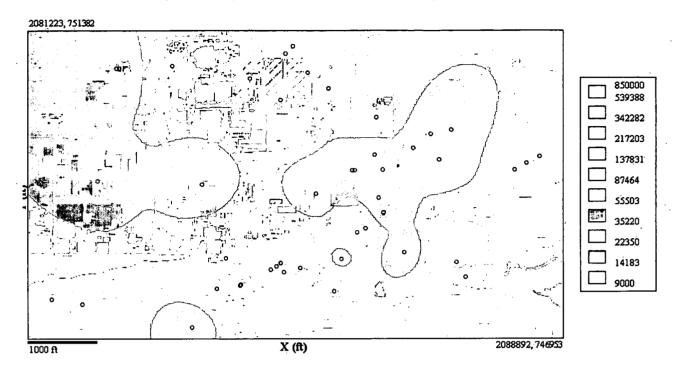
## Isopleth Map of pH ug/L During 1994-1995



b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

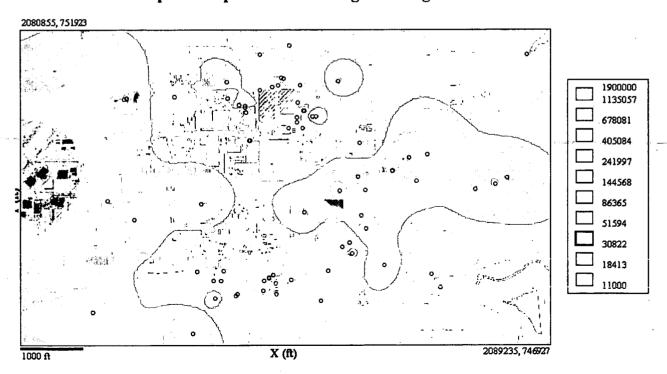


## Isopleth Map of SULFATE ug/L During 1986-1987

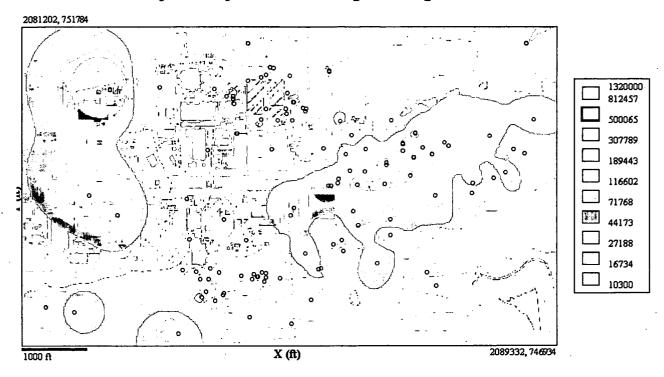


b All Set2 Sitewide 1986-1987 in Biodegradation mdb

## Isopleth Map of SULFATE ug/L During 1988-1989

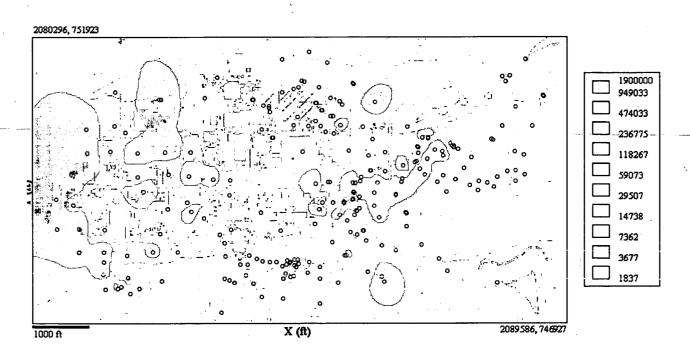


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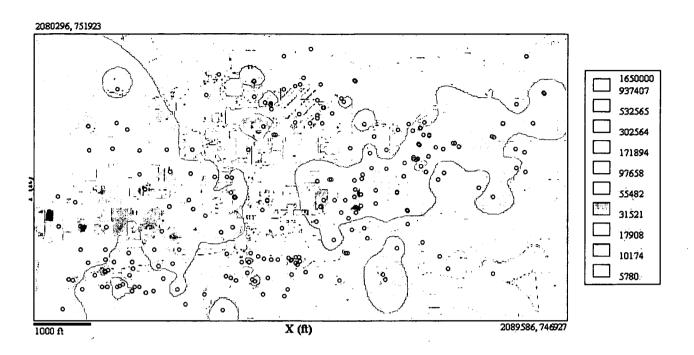


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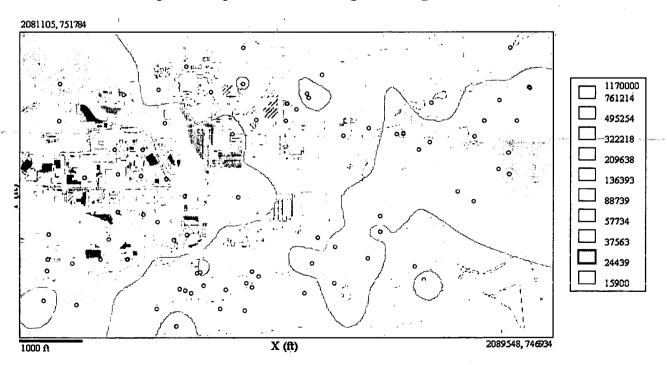


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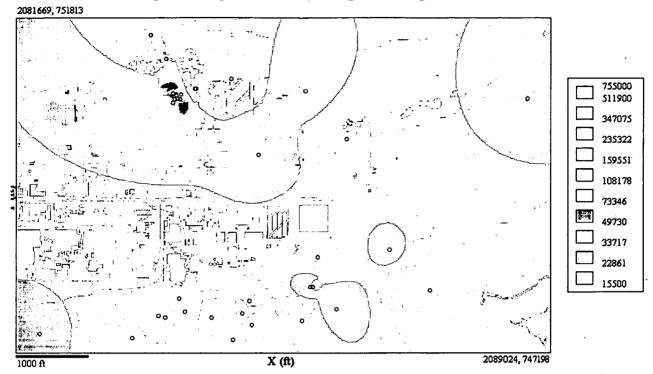


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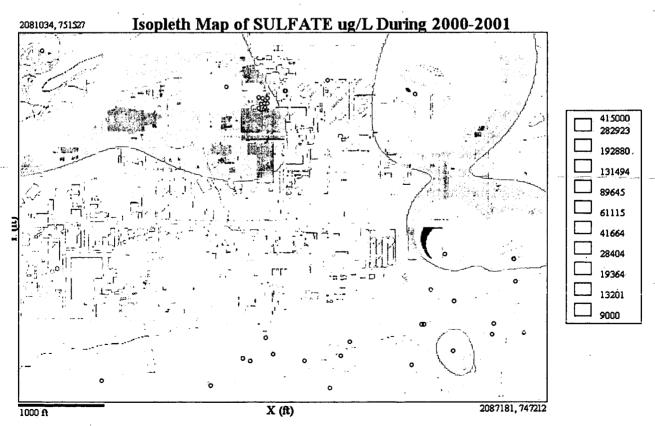
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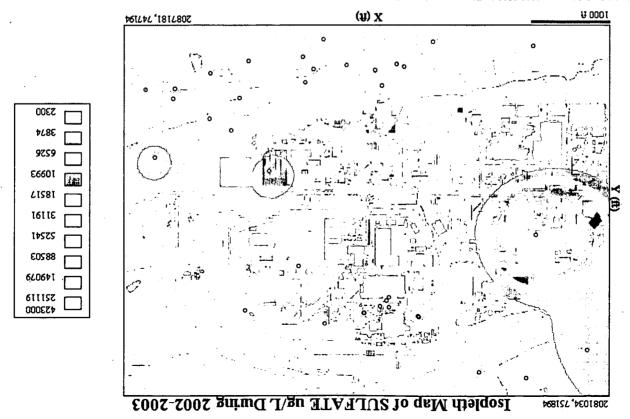
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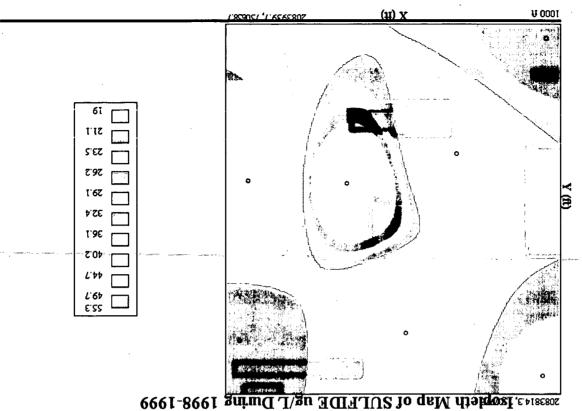
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b All Set2 Sitewide 2000-2001 in Biodegradation.mdb

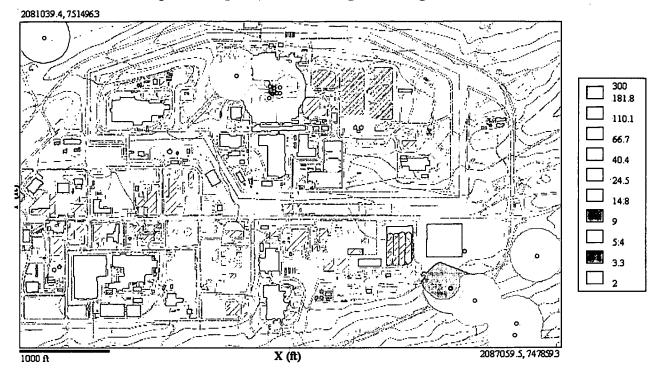


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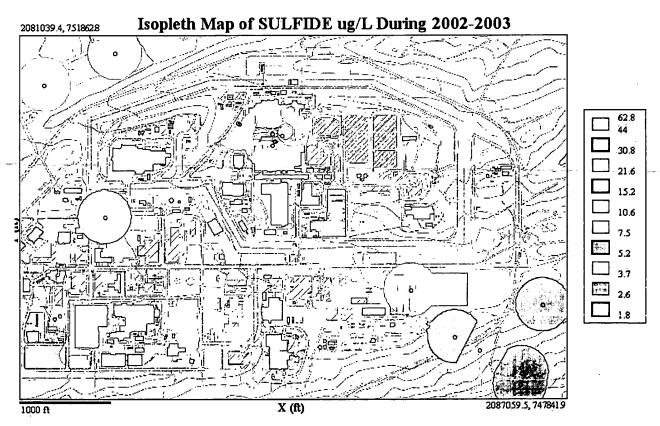


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## Isopleth Map of SULFIDE ug/L During 2000-2001

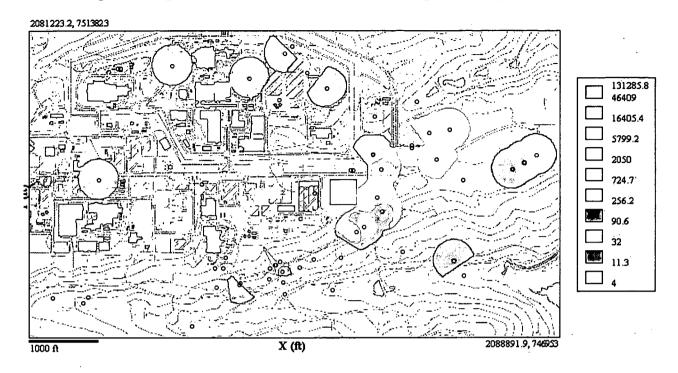


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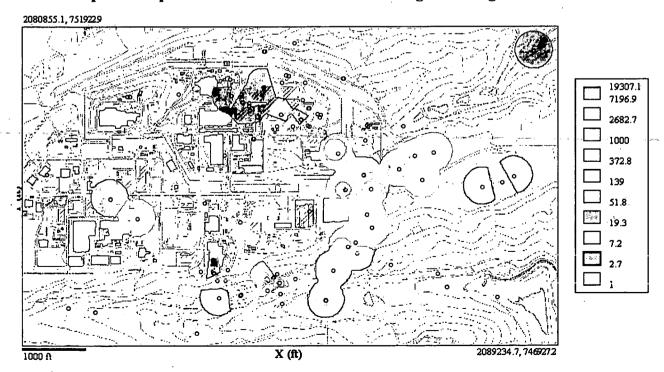
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#### Isopleth Map of TETRACHLOROETHENE ug/L During 1986-1987

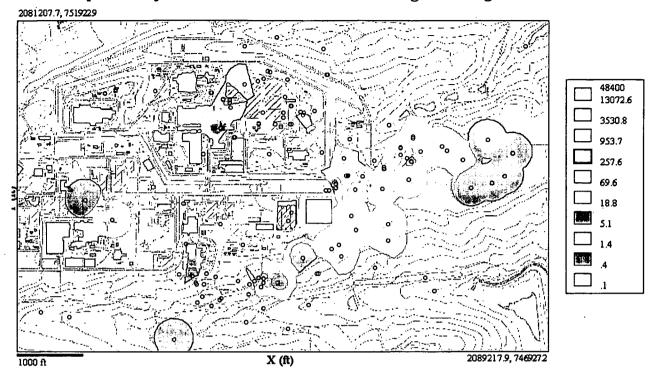


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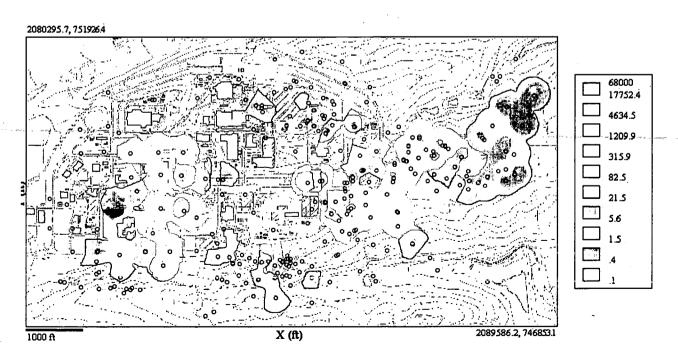


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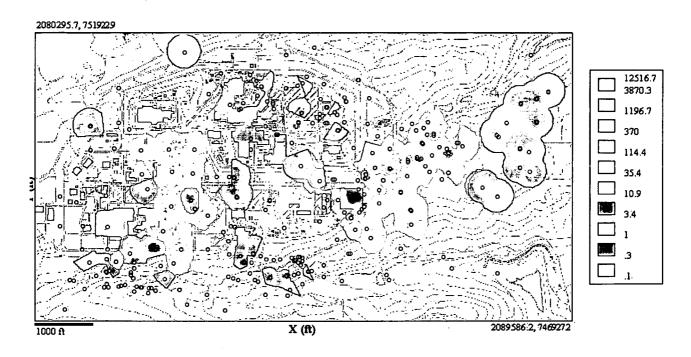


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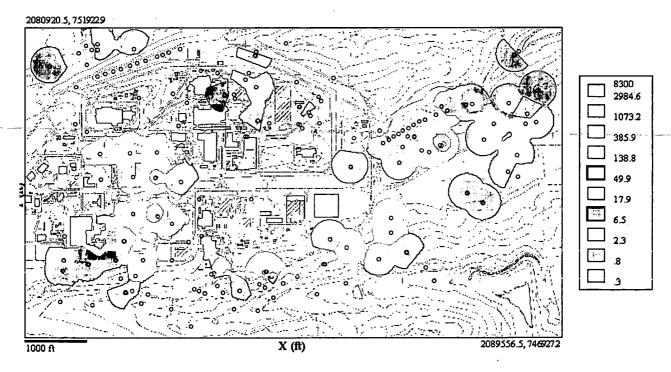


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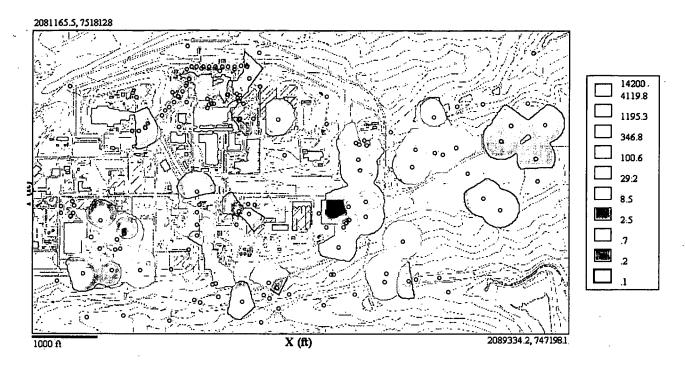


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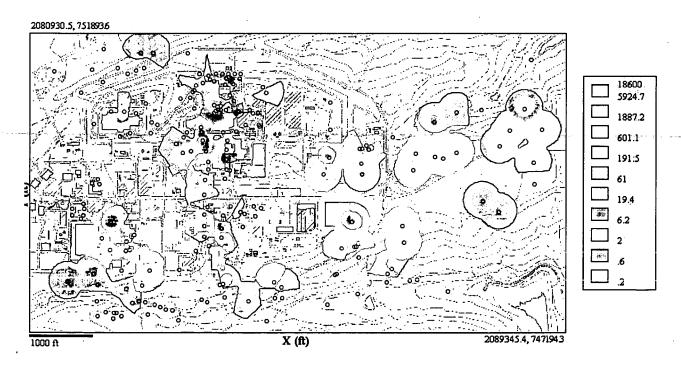


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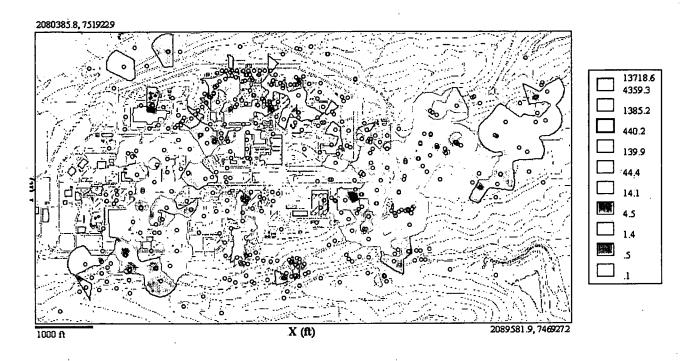


b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

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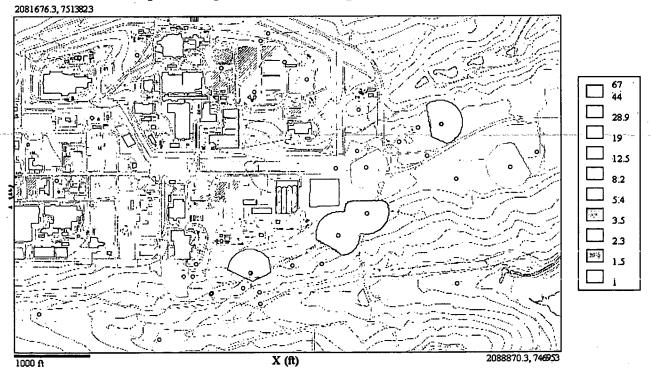


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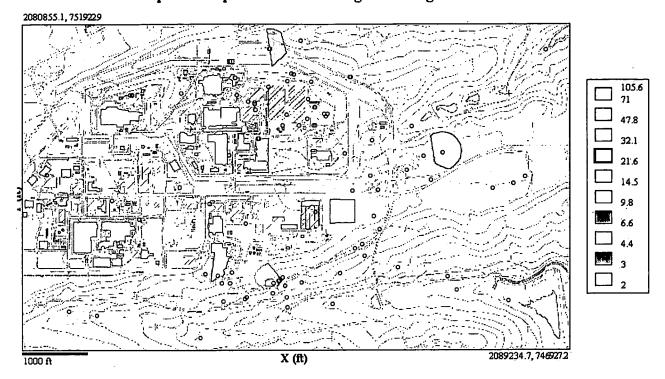


ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

## Isopleth Map of TOLUENE ug/L During 1986-1987

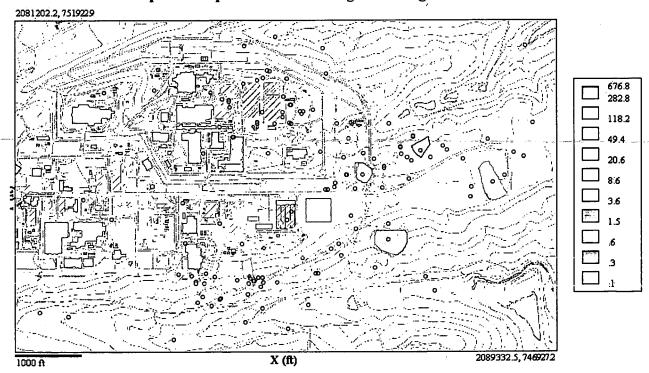


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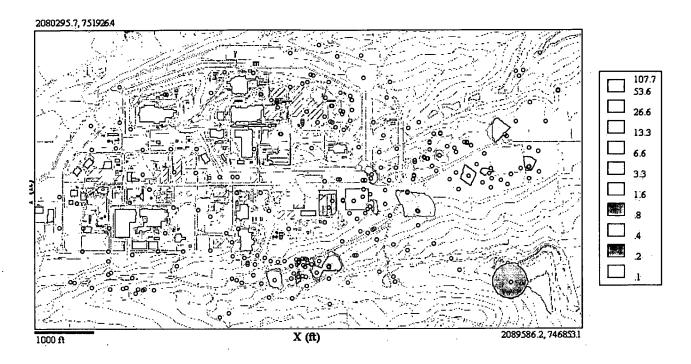


b All Set2 Sitewide 1988-1989 in Biodegradation.mdb

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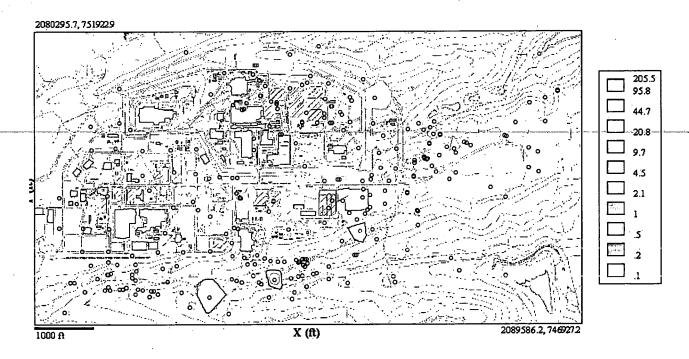


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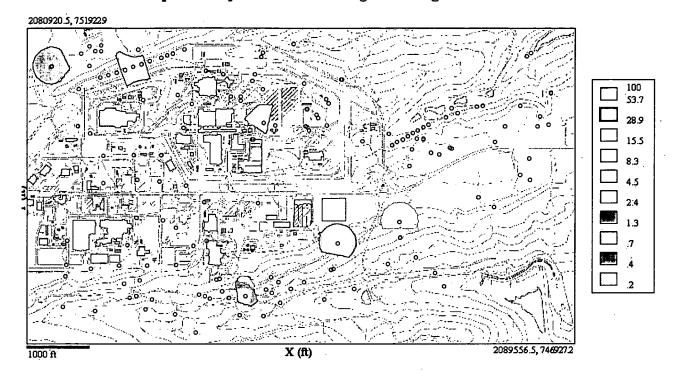


b All Set2 Sitewide 1992-1993 in Biodegradation.mdb

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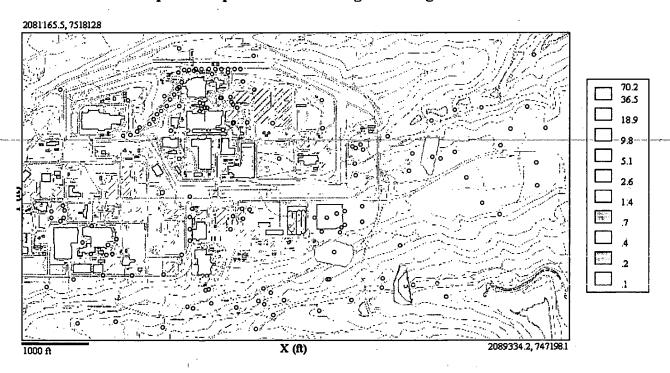


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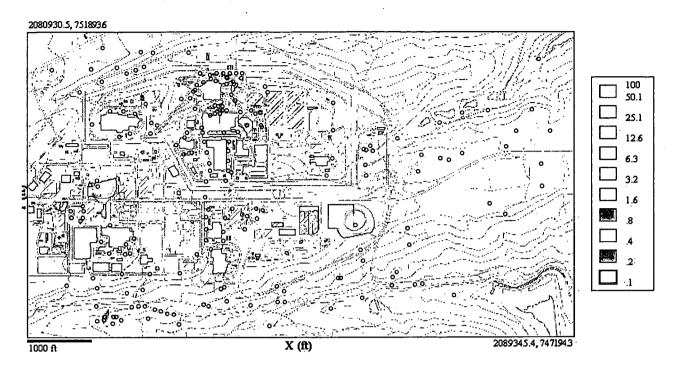


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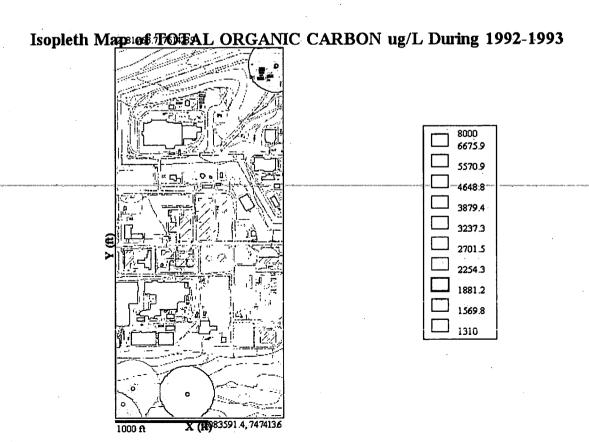
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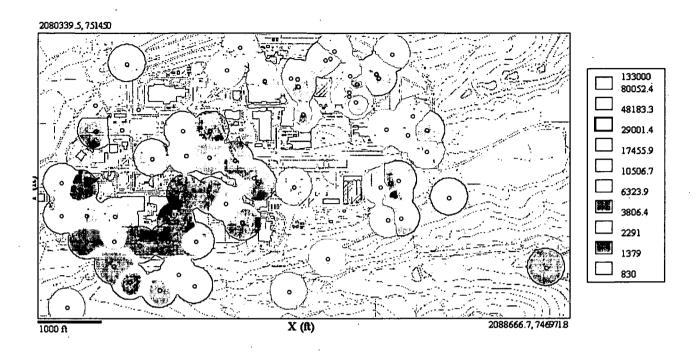
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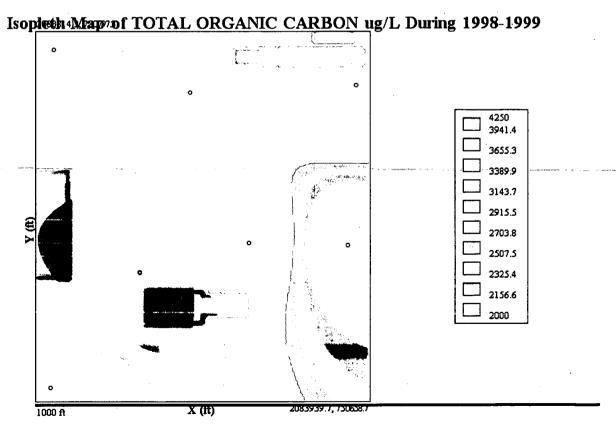
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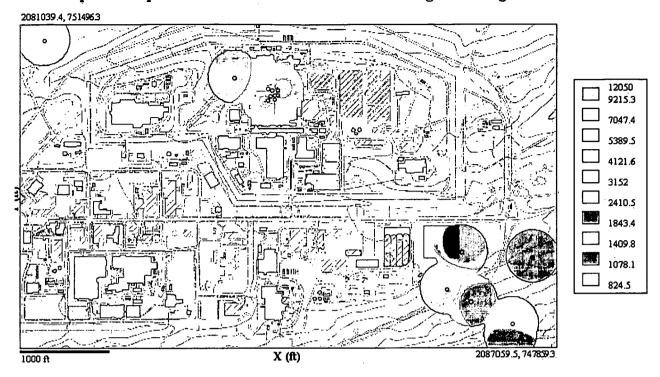
## Isopleth Map of TOTAL ORGANIC CARBON ug/L During 1994-1995



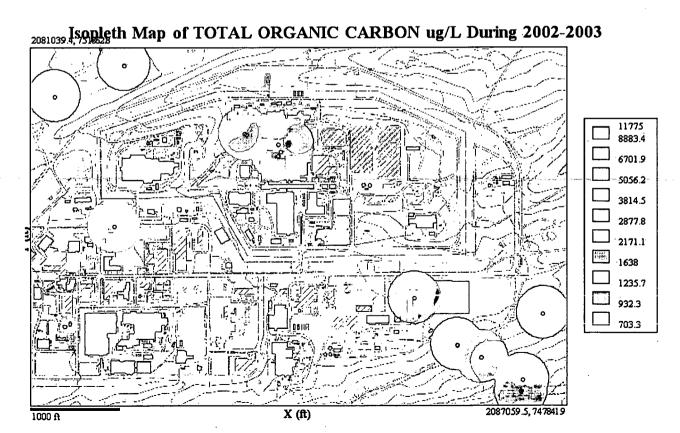
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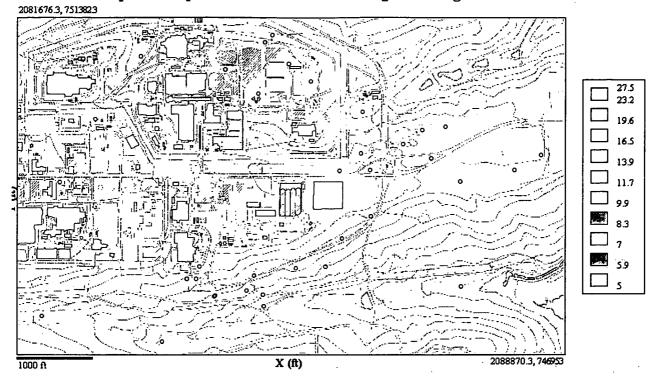
# Isopleth Map of TOTAL ORGANIC CARBON ug/L During 2000-2001



b All Set2 Sitewide 2000-2001 in Biodegradation mdb

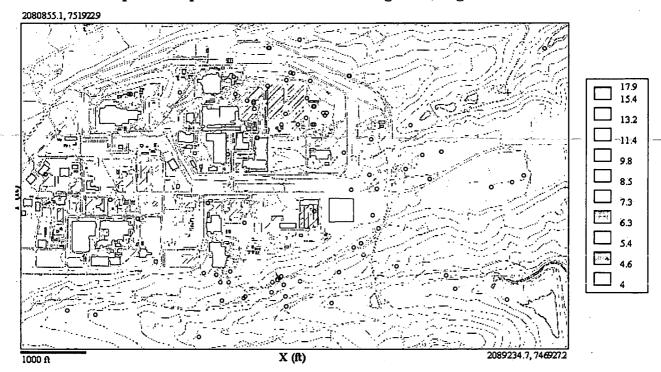


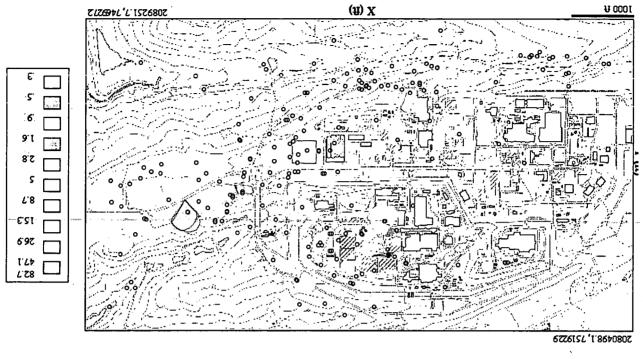
Isopleth Map of TOTAL XYLENES ug/L During 1986-1987



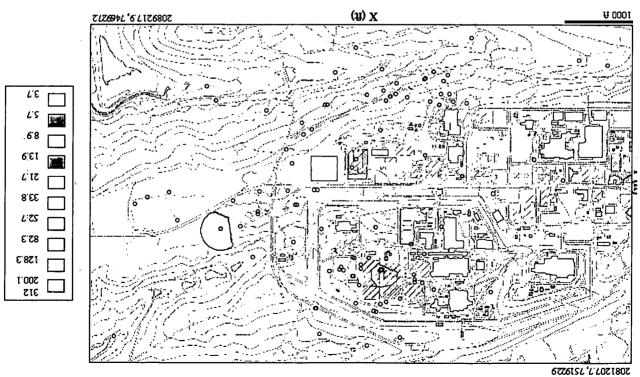
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Isopleth Map of TOTAL XYLENES ug/L During 1988-1989





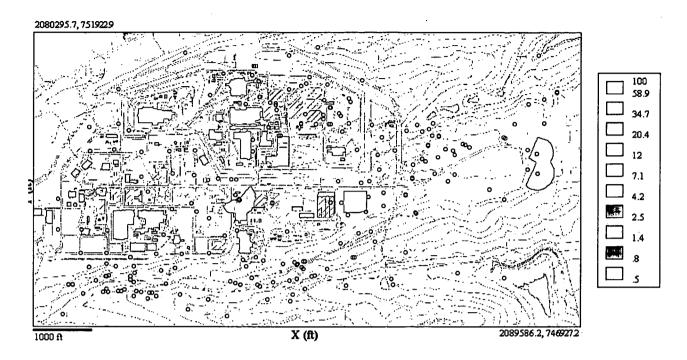
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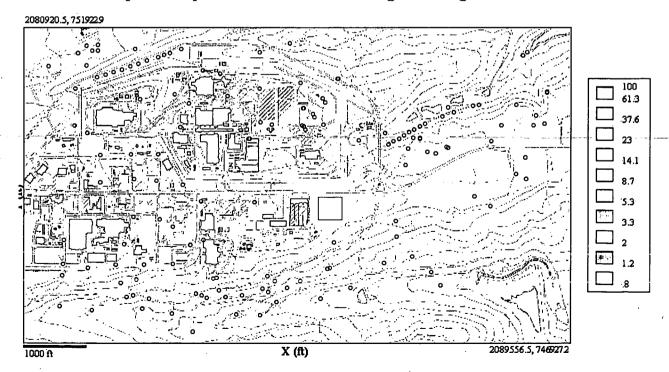
Isopleth Map of TOTAL XYLENES ug/L During 1990-1991

## Isopleth Map of TOTAL XYLENES ug/L During 1994-1995

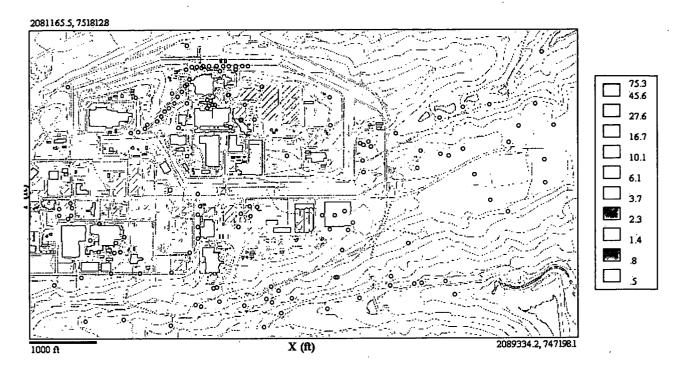


b All Set2 Sitewide 1994-1995 in Biodegradation.mdb

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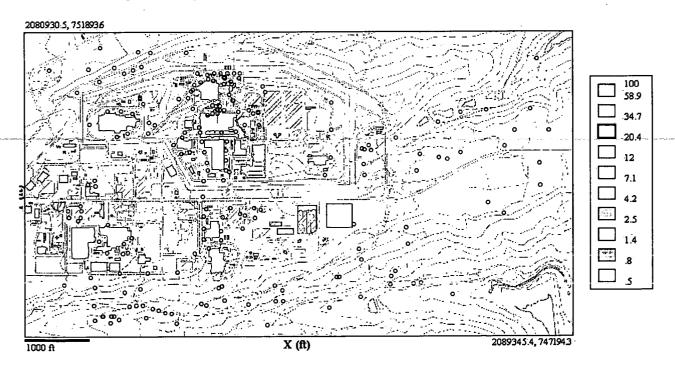


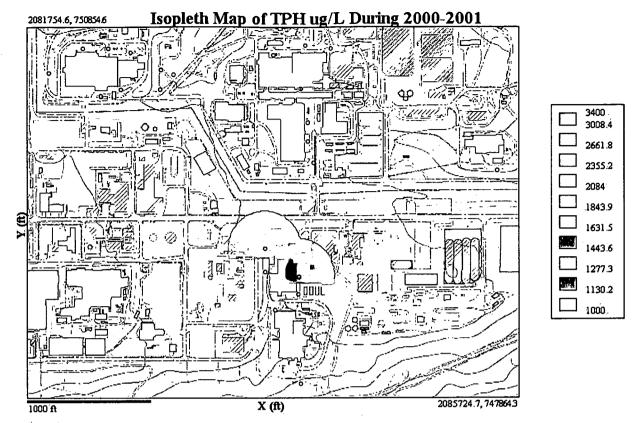
# Isopleth Map of TOTAL XYLENES ug/L During 1998-1999



b All Set2 Sitewide 1998-1999 in Biodegradation.mdb

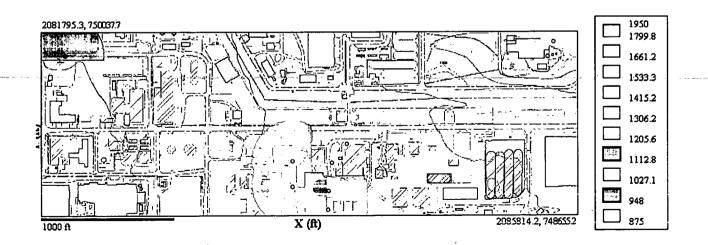
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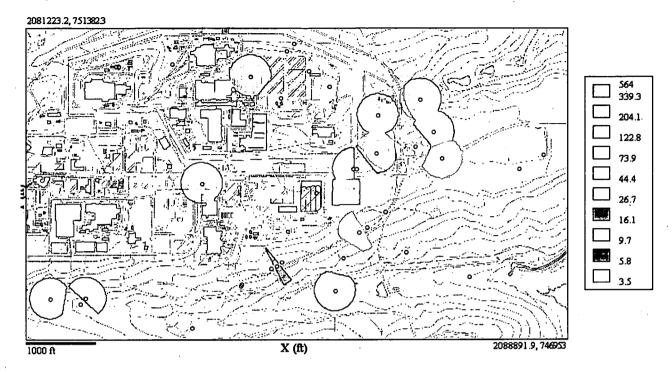


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#### Isopleth Map of TPH ug/L During 2002-2003

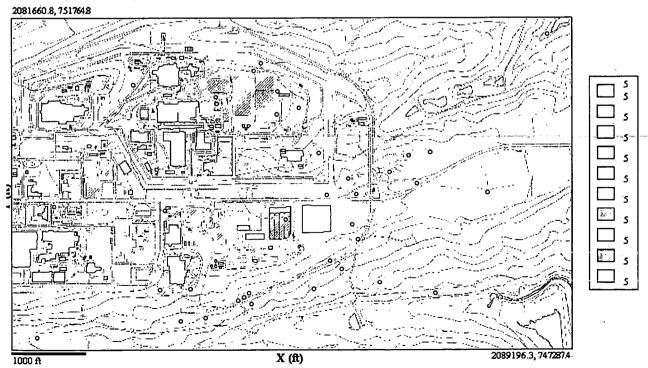


#### Isopleth Map of trans-1,2-DICHLOROETHENE ug/L During 1986-1987

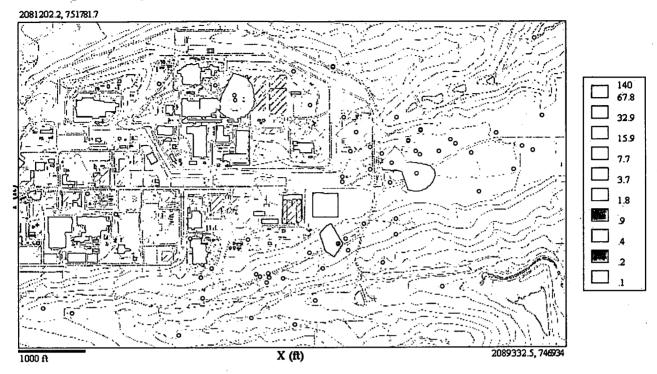


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

# Isopleth Map of trans-1,2-DICHLOROETHENE ug/L During 1988-1989

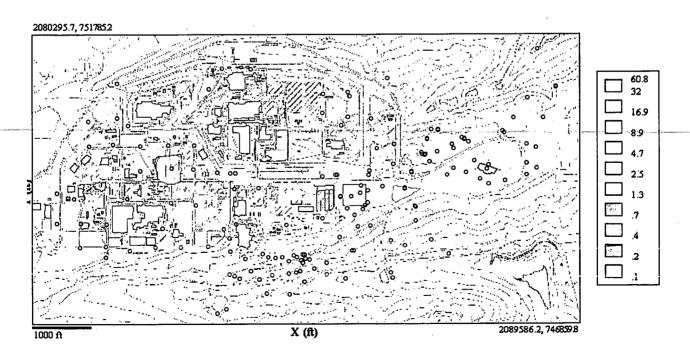


Isopleth Map of trans-1,2-DICHLOROETHENE ug/L During 1990-1991

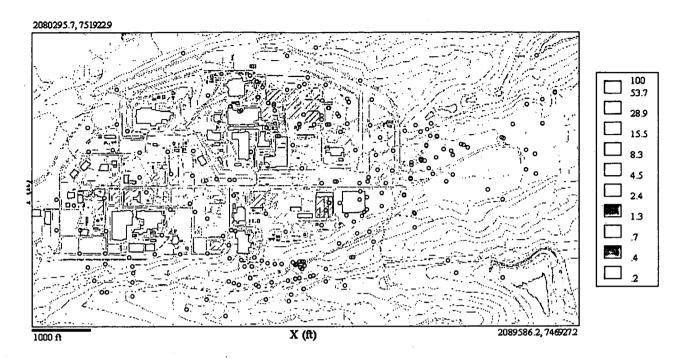


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Isopleth Map of trans-1,2-DICHLOROETHENE ug/L During 1992-1993

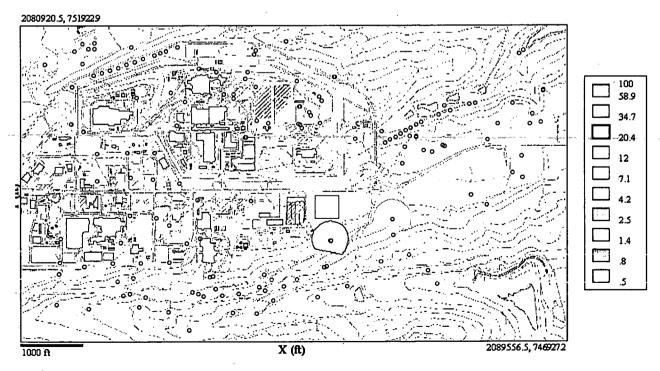


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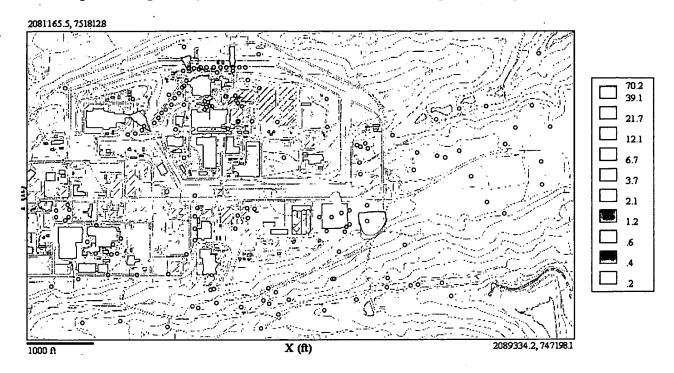


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# Isopleth Map of trans-1,2-DICHLOROETHENE ug/L During 1996-1997

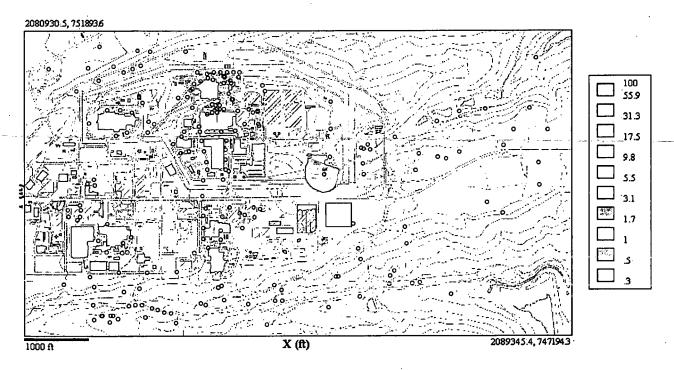


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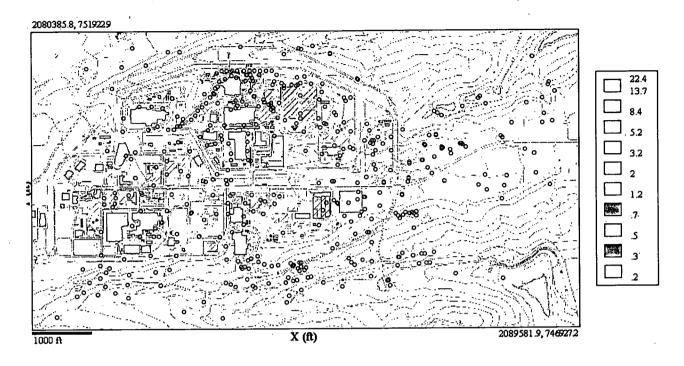


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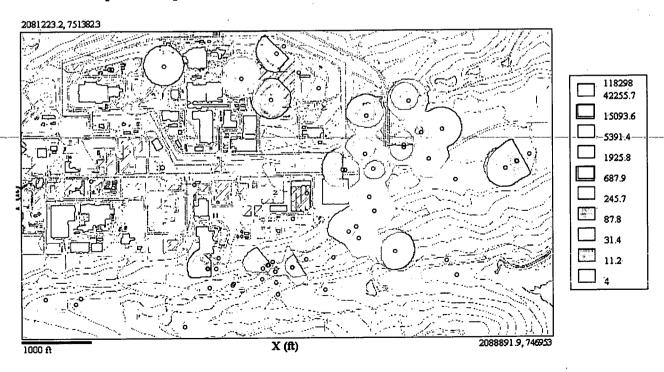


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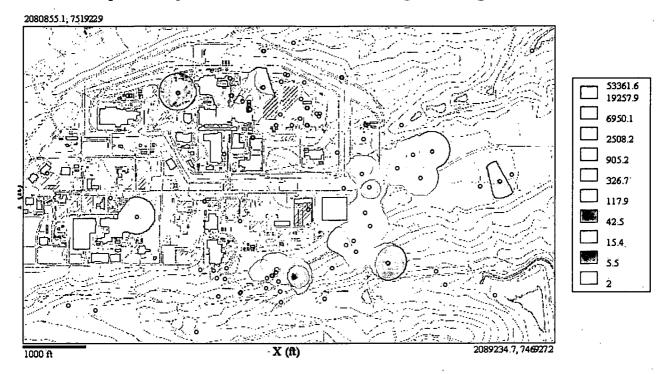


ab All Set2 Sitewide 2002-2003 in Biodegradation.mdb

# Isopleth Map of TRICHLOROETHENE ug/L During 1986-1987

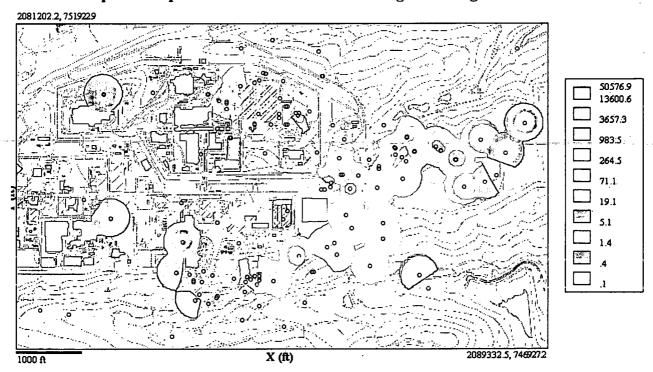


# Isopleth Map of TRICHLOROETHENE ug/L During 1988-1989

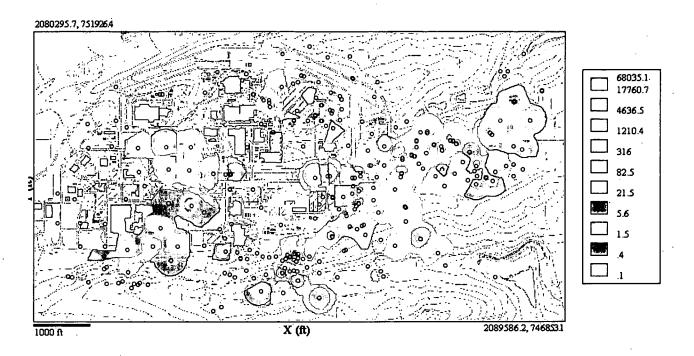


b All Set2 Sitewide 1988-1989 in Biodegradation.mdb

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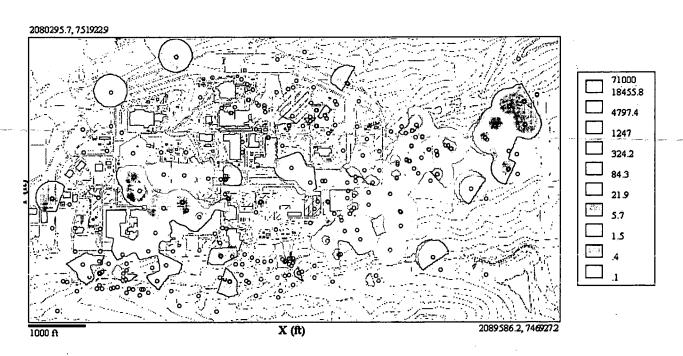


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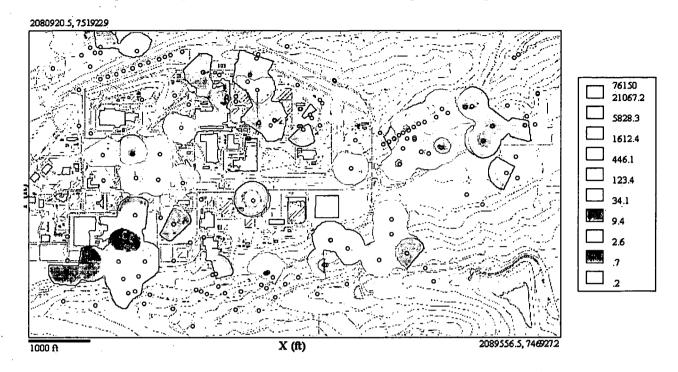


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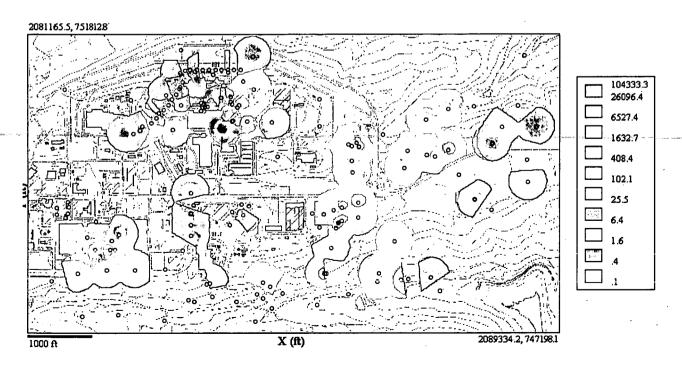


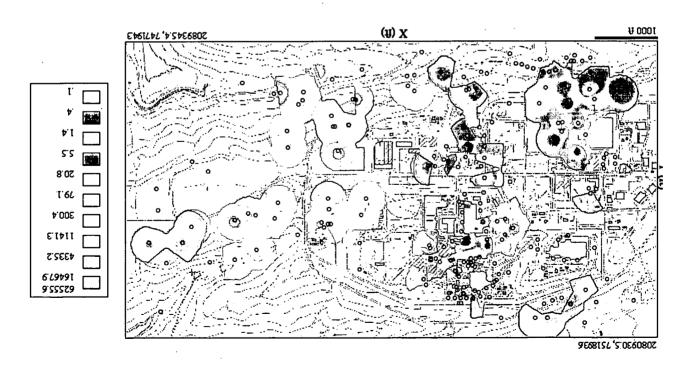
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b All Set2 Sitewide 1996-1997 in Biodegradation.mdb

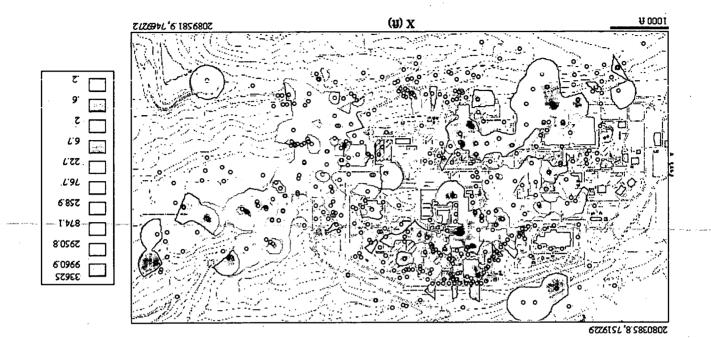
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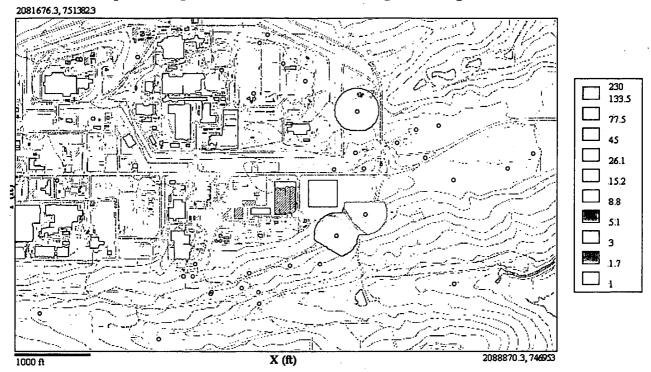


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Isopleth Map of TRICHLOROETHENE ug/L During 2002-2003

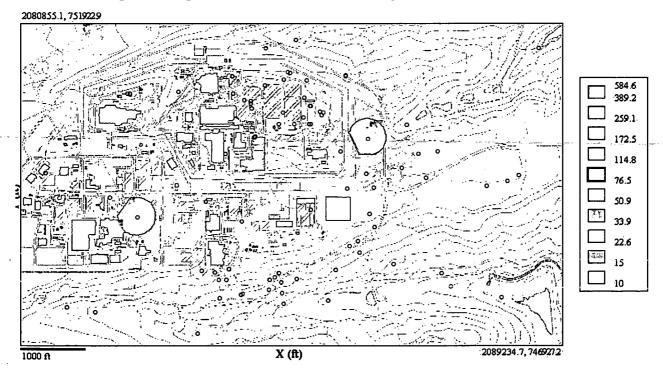


#### Isopleth Map of VINYL CHLORIDE ug/L During 1986-1987

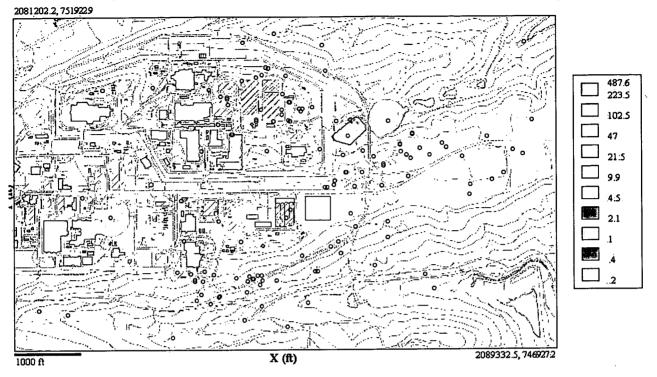


b All Set2 Sitewide 1986-1987 in Biodegradation.mdb

#### Isopleth Map of VINYL CHLORIDE ug/L During 1988-1989

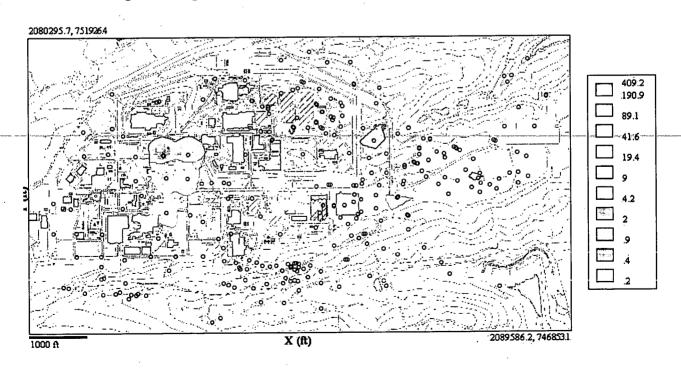


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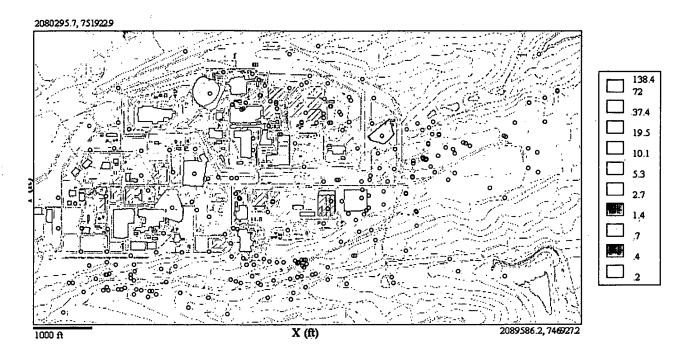


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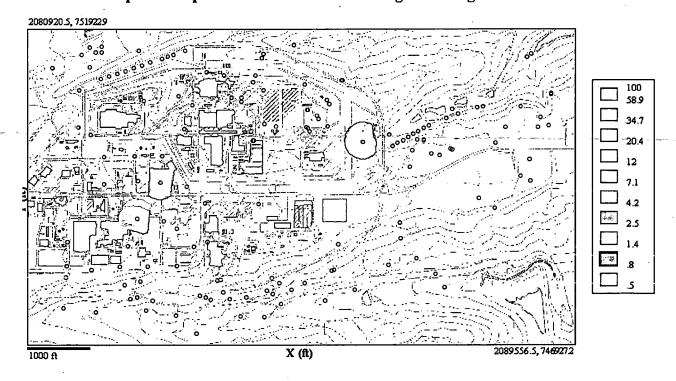


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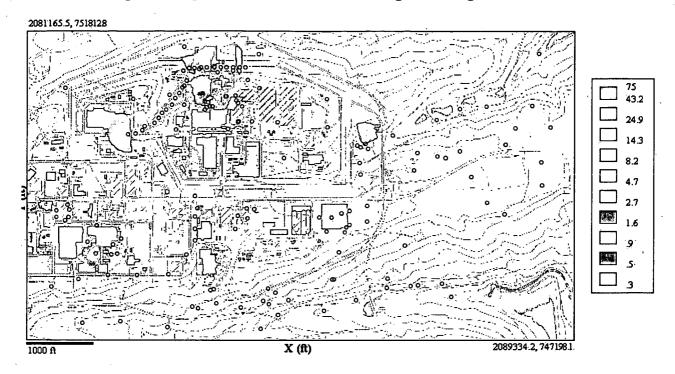


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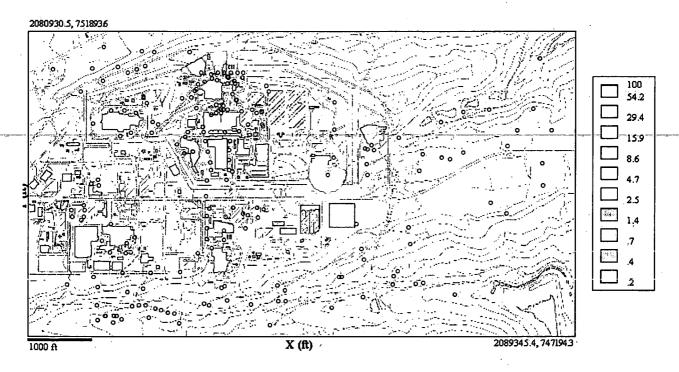


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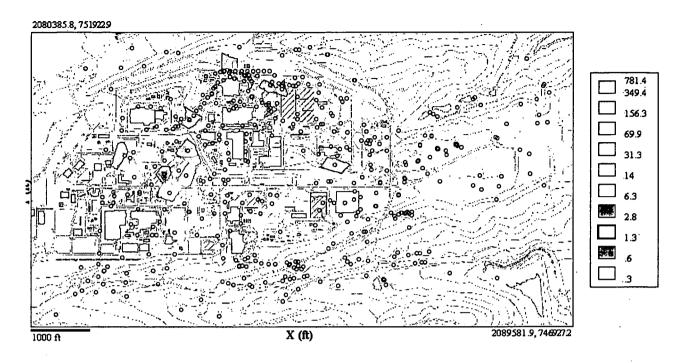


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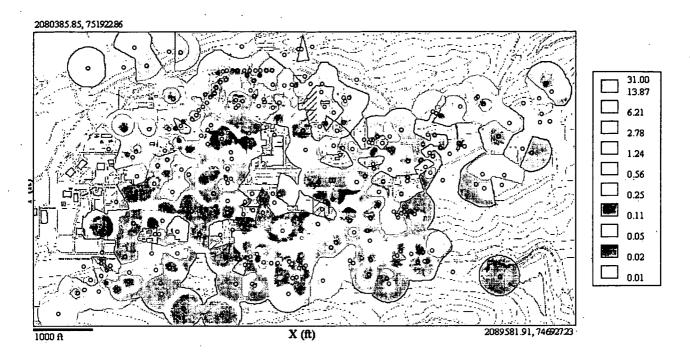


# Isopleth Map of VINYL CHLORIDE ug/L During 2002-2003



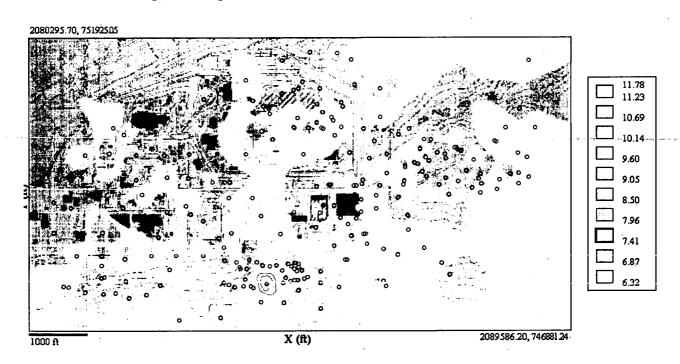
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# Isopleth Map of FERROUS IRON mg/L During 2002-2003

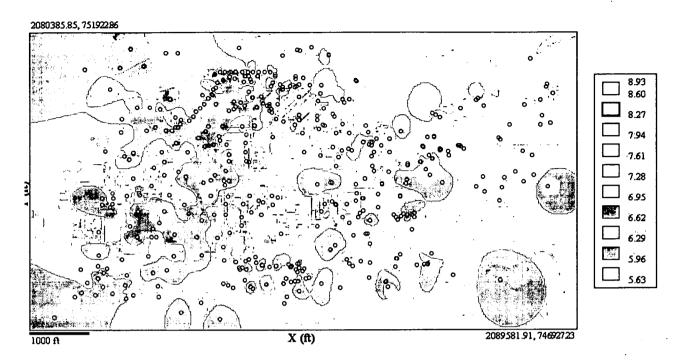


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#### Isopleth Map of Field-Measured PH During 1992-1993

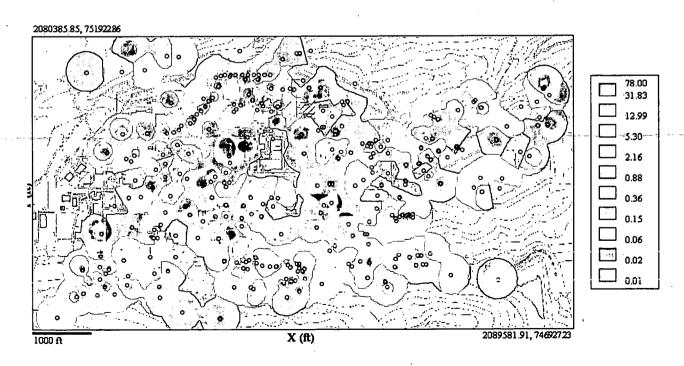


#### Isopleth Map of Field-Measured PH During 2002-2003

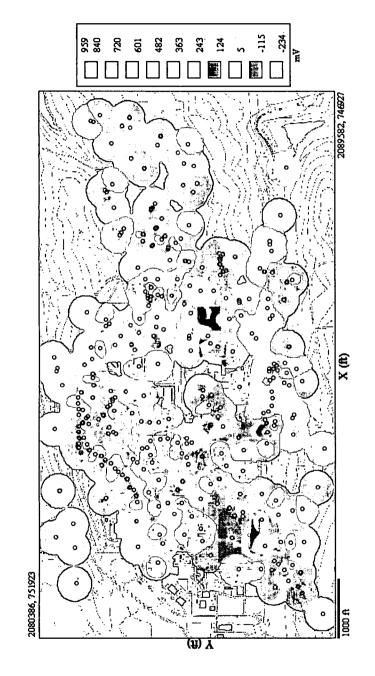


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#### Isopleth Map of IRON mg/L During 2002-2003

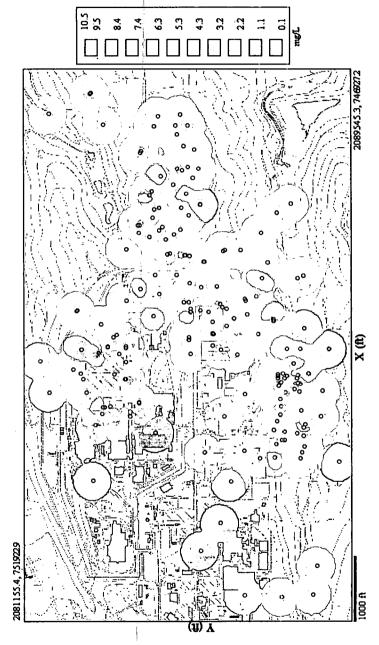


Isopleth Map of ORP in Groundwater During 2002-2003



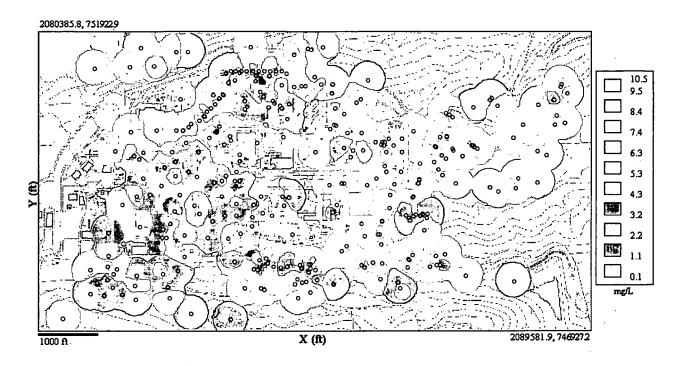
Field All Set2 Sitewide 2002-2003 in Biodegradation mdb

Map of DO in Groundwater During 1992-1993



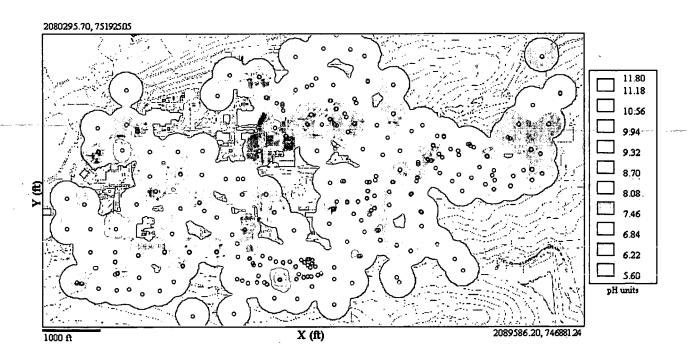
Field All Set2 Sitewide 1992-1993 in Biodegradation.mdb

Map of DO in Groundwater During 2002-2003

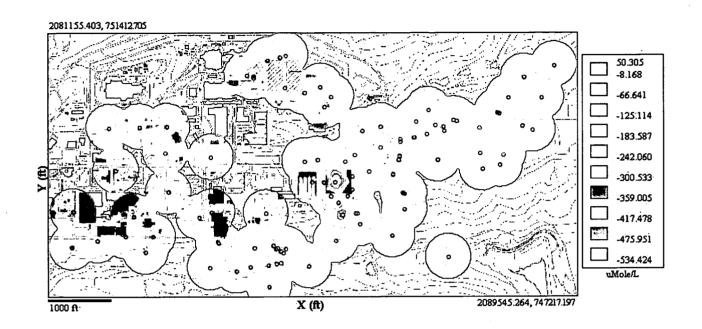


Field All Set2 Sitewide 2002-2003 in Biodegradation.mdb

Map of Field-Measured pH in Groundwater During 1992-1993

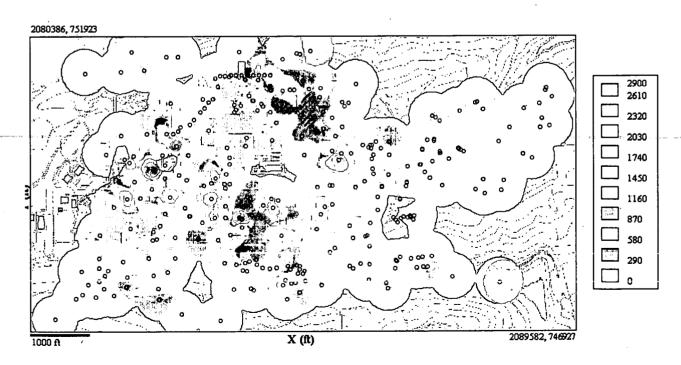


#### Change in Total CAH uMoles in Groundwater During the Past Decade

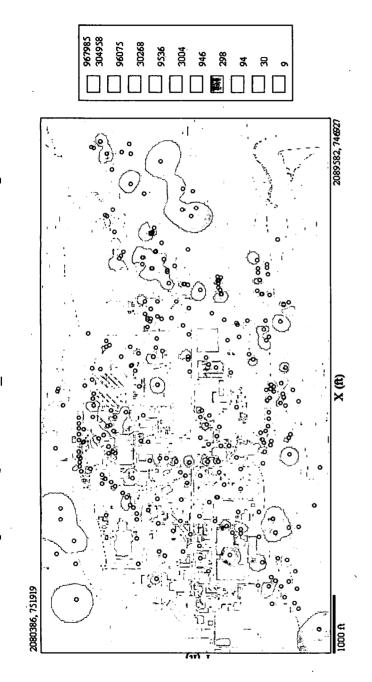


VOC uMole Changes after 10 Years in Biodegradation.mdb

#### Isopleth Map of SULFATE mg/L During 2002-2003

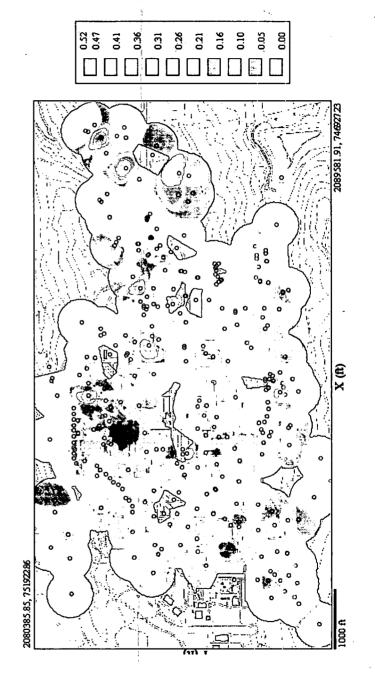


Isopleth Map of Sulfate\_Sulfide Mole Ratios During 2003

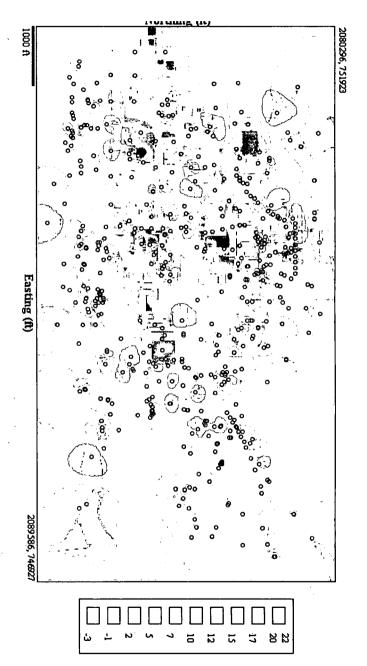


14\_Sulfide Ratios During 2003 in Biodegradation mdt

Isopleth Map of SULFIDE mg/L During 2002-2003

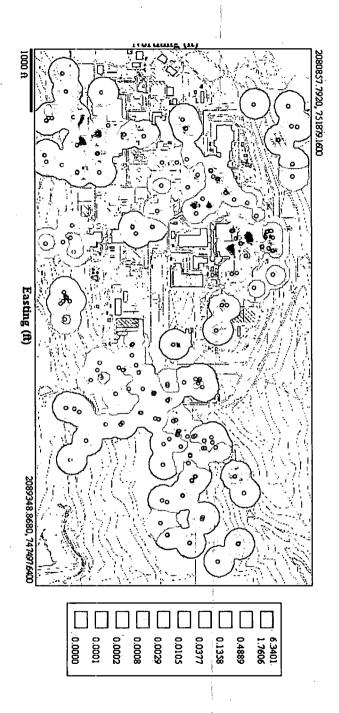


# Isopleth Map of Wiedemeier Scores

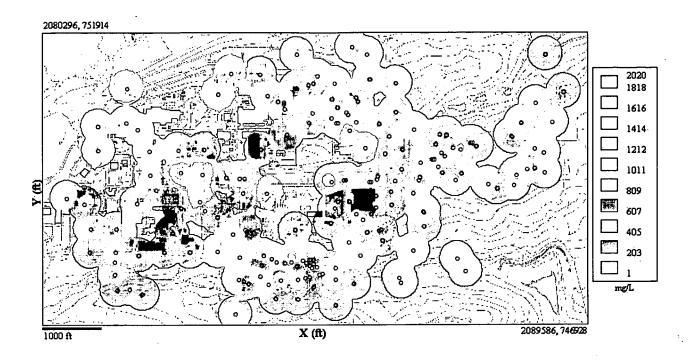


demeier Scores4 in Biodegradation mdb

# Map of 1,1,1-TRICHLOROETHANE Mean %Solubility, Time Averaged

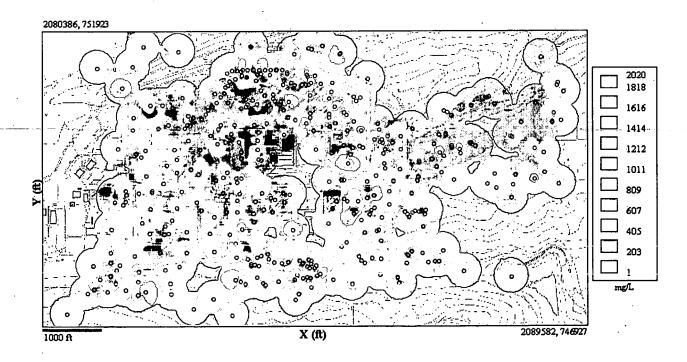


Map of Alkalinity in Groundwater During 1992-1993

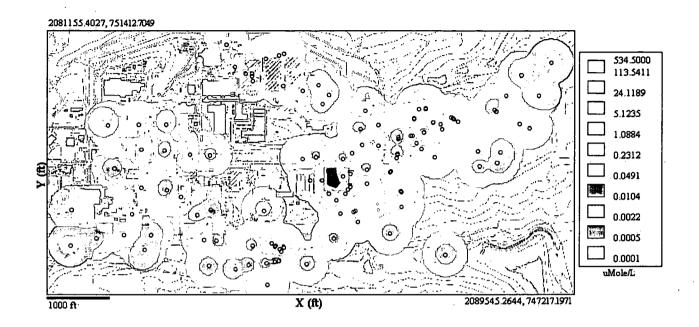


Field All Set2 Sitewide 1992-1993 in Biodegradation.mdb

Map of Alkalinity in Groundwater During 2002-2003

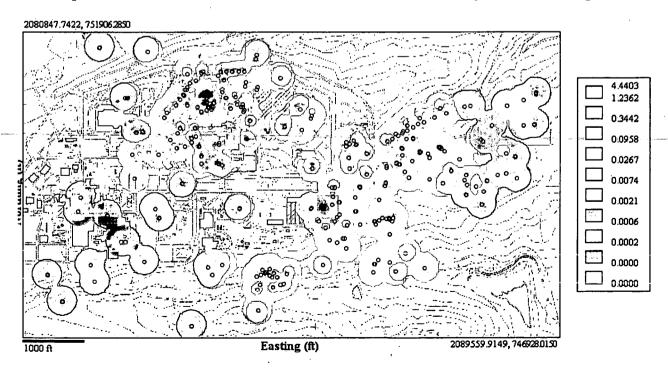


# Map of Attenuation (Decreases) in Total CAH uMoles During the Past Decade

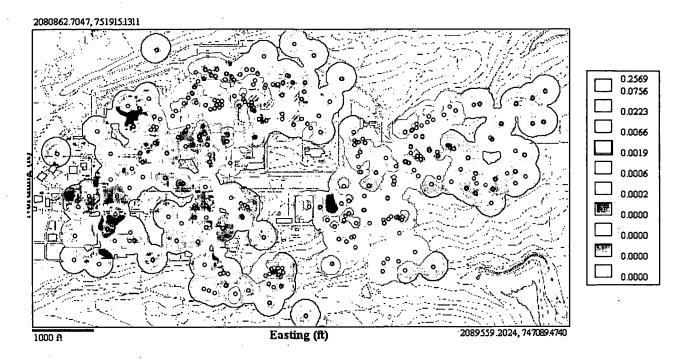


VOC uMole Changes after 10 Years in Biodegradation.mdb

Map of CARBON TETRACHLORIDE Mean %Solubility, Time Averaged

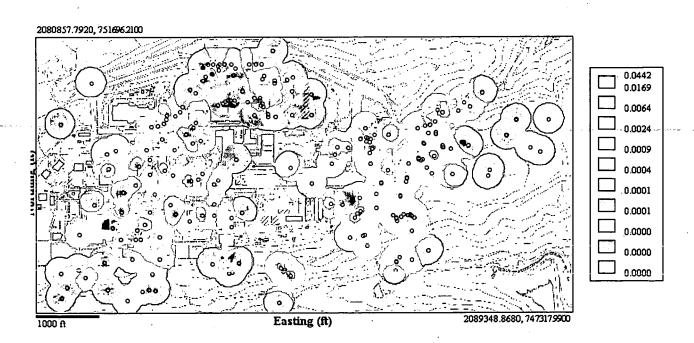


Map of CHLOROFORM Mean %Solubility, Time Averaged

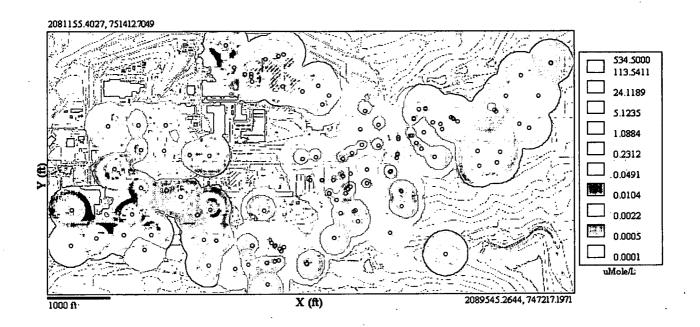


ISU CI-VOCs NAPLs Set1 in Biodegradation.mdb

Map of cis-1,2-DICHLOROETHENE Mean %Solubility, Time Averaged

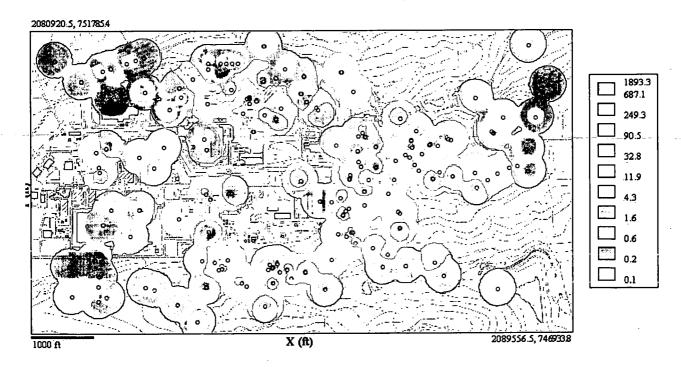


# Map of Increases in Total CAH uMoles During the Past Decade

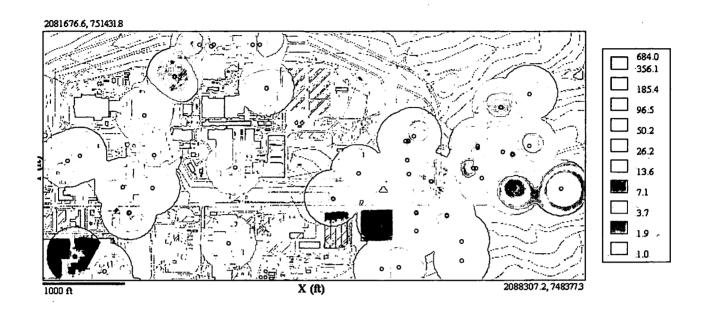


VOC uMole Changes after 10 Years in Biodegradation.mdb

Map of Maximum BTEX Concentrations in RFETS Groundwater

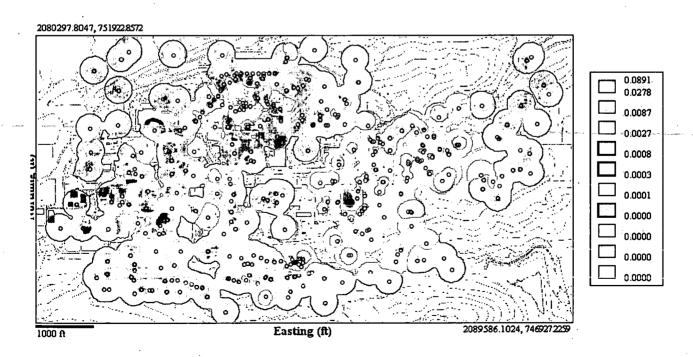


#### Map of Maximum cis-trans 1,2 DCE Ratios Across All Time Periods

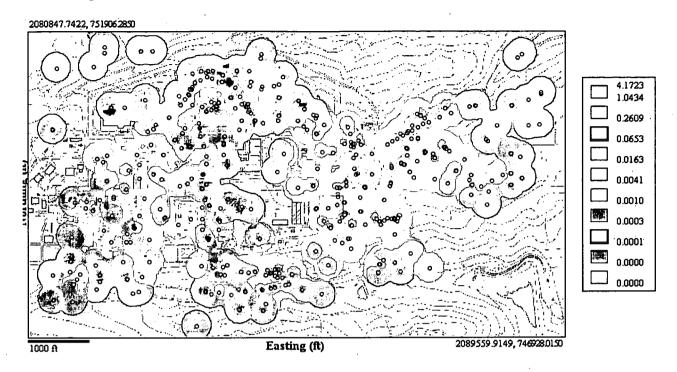


-trans Max ratios all periods DW Contour in Biodegradation.mdb

# Map of METHYLENE CHLORIDE Mean %Solubility, Time Averaged

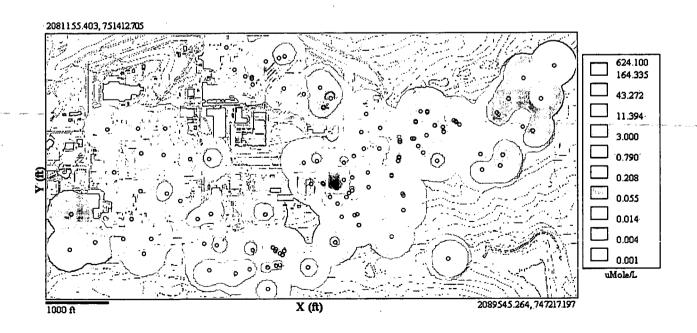


Map of TETRACHLOROETHENE Mean %Solubility, Time Averaged

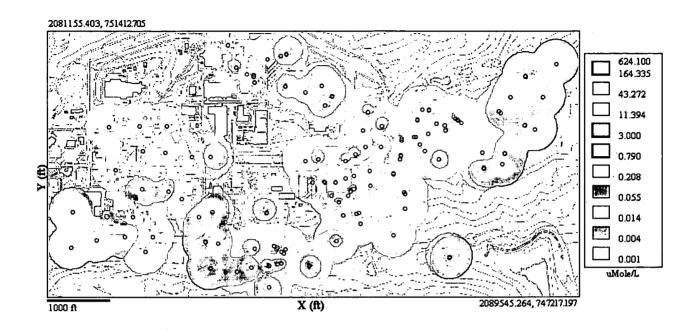


HSU CI-VOCs NAPLs Set1 in Biodegradation.mdb

Map of Total CAH uMoles in Groundwater During 1992-1993

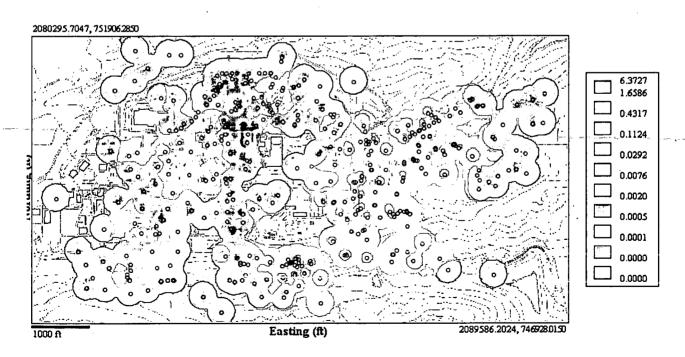


#### Map of Total CAH uMoles in Groundwater During 2002-2003



VOC uMole Changes after 10 Years in Biodegradation.mdb

# Map of TRICHLOROETHENE Mean %Solubility, Time Averaged



#### APPENDIX G

SITE-SPECIFIC WATER QUALITY ACTION LEVELS AND STANDARDS

#### Appendix G

#### Site-Specific Water Quality Action Levels and Standards

This appendix discusses the rationale behind the use of RFCA groundwater action levels in this report and summarizes Site-specific water quality criteria.

RFCA is a legal agreement between DOE, CDPHE, and EPA that governs the remediation and closure of RFETS (CDPHE, DOE, EPA, 1996). RFCA Attachment 5, revised May 28, 2003, describes the action levels and standards framework (ALF) for groundwater and surface water quality at RFETS (CDPHE, DOE, EPA, 2003). The ALF establishes action levels for Site groundwater and both action levels and cleanup standards for Site surface water.

Surface water standards are enforceable and are applied at points of compliance (POCs) at the outfalls of ponds A-4, B-5 and C-2. However, surface water standards are not directly applied to groundwater. During the period of active remediation groundwater action levels apply and must be protective of surface water standards and quality as well as ecological resources (CDPHE, DOE, EPA, 2003). "Surface water protection [is] the only use classification for groundwater at RFETS" (CDPHE, DOE, EPA, 2003).

Groundwater action levels use a two-tiered approach. Tier II groundwater action levels are based on maximum contaminant levels (MCLs). Tier II groundwater action levels are "designed to prevent surface water from exceeding surface water standards/action levels by triggering ground water management actions..." (CDPHE, DOE, EPA, 2003).

Tier I groundwater action levels are, by definition, 100 times larger than the Tier II action levels. Tier I action levels are "designed to identify high concentration groundwater sources that should be addressed through accelerated actions" (CDPHE, DOE, EPA, 2003, p.5-11). If Tier I action levels are exceeded by a CAH (or other COC) in groundwater, a water quality evaluation is required to determine if remedial action is necessary to protect surface water (CDPHE, DOE, EPA, 2003). Lastly, "All final remedies must be designed to protect surface water for any use as measured at the nearest and/or most directly impacted surface water..." (CDPHE, DOE, EPA, 2003, p.5-9).

Based on the RFCA, this evaluation compared CAH concentrations in groundwater with the RFCA Tier I and Tier II groundwater action levels. Action levels for CAHs in groundwater are tabulated in Table G-1. For comparison, this table also lists the Site-specific surface water standards and draft preliminary surface

water remediation goals (PRGs) developed by ER in February 2004, although the PRGs are not used for comparison in this report.

RFCA Attachment 5 also states, "Ground water plumes that can be shown to be stationary and do not therefore present a risk to surface water, regardless of their contaminant levels, will not require remediation or management" (CDPHE, DOE, EPA, 2003). Therefore, this evaluation also examines CAH plume stability through time.

Table G-1 Site-Specific Water Quality Action Levels and Standards

CAH Acronym	САН	RFCA SW Standards Segments 4a and 4b and Action Levels Segment 5 RFCA Attachment 5 (µg/L)	RFCA SW Temporary Modification For Segment 5 Until 12/31/09 (µg/L)	Tier II Groundwater Action Level RFCA Attachment 5 (μg/L)	Tier I Groundwater Action Level RFCA Attachment 5 (μg/L)	Draft Surface Water PRGs for Wildlife Refuge Worker At 1E-6 Risk (µg/L)
CT	carbon tetrachloride	0.25	5	. 5	500	584
CE	chloroethane	29.4		29.4	2,940	26,200
CF	chloroform	5.7	i i	100	10,000	20,300
CM	chloromethane	5.7		6.55	655	5,840
1,1-DCA	1,1-dichloroethane	3,650		3,650	365,000	203,000
1,2-DCA	1,2-dichloroethane	0.38	5	. 5	500	834
1,1-DCE	1,1-dichloroethene	7	7	7	700	127
cis-1,2-DCE	cis-1,2-dichloroethene	70		70	7,000	18,300
trans-1,2-DCE	trans-1,2-dichloroethene	100		70	7,000	18,300
MC	methylene chloride	4.7	* *	5	500	10,100
VC	vinyl chloride	2		. 2	200	105
TCE	trichloroethene	2.7	5	5	500	190
PCE	tetrachloroethene	0.8	5	5	500	1,460
1,1,1-TCA	1,1,1-trichloroethane	200		200	20,000	568,000
1,1,2-TCA	1,1,2-trichloroethane	<b>3</b>		5	500	1,330

Segment 4a - Woman and Walnut Creeks upstream of Standley Lake and Great Western Reservoir, except Segments 4b and 5.

Segment 4b - North Walnut Creek & Walnut Creek from Pond A-4 outlet to Indiana Street.

Segment 4b - South Walnut Creek & Walnut Creek from Pond B-5 outlet to Indiana Street.

Segment 5 - All tributaries of Woman Creek & North & South Walnut Creek upstream of the outlets of Ponds A-4, B-5, C-2.

#### APPENDIX H

CAH COMPOUNDS NOT EVALUATED IN THIS REPORT

# Appendix H CAH Compunds Not Evaluated in This Report

Other CAHs exist that are not discussed in this report, although these CAHs have been analyzed in groundwater samples collected at the RFETS. These compounds were not discussed because they have only been detected in groundwater at a few wells, were detected at low concentrations, were not detected, or lack a Tier II groundwater action level. Hydrocarbons containing substituted bromine, fluorine, or iodine were also not reviewed in this report. Table H-1 summarizes the historical data for these analytes that occurred in SWD as of November 2003.

Table H-1 CAHs of Relatively Minor Significance in Groundwater at the RFETS

САН	Number of Detects > Reporting Limit Since 1986	Wells with Relatively Large Concentrations	Period of Relatively Large Concentrations	Tier II Action Level (µg/L)	Notes	
1,1,1,2- tetrachloroethane	32	Wells 07391 and 00897	2003	None	Maximum historical concentrations at well 07391 and 00897 are 5.8 and 4.0 μg/L, respectively	
1,1,2,2- tetrachloroethane	26	Wells B206189 and 07391	1989 to 1992	0.426	Well B206189 had a maximum historical concentration of 190 and 180 μg/L, respectively. The maximum concentration at either well since 1994 is 3 μg/L.	
1,1,2- trichloroethane	116	Wells 0974, 4387, 24193, 07391, P115589, and 891COLWEL	1980's	5	Well 0974 had a concentration of 14,740 μg/L in 1988 and has decreased to < 72 μg/L by 1992. Maximum concentration during 2003 at well 07391 is 30 μg/L	
1,1-dichloropropene	13	Wells 02991, 03391, 07891	1992	None	Maximum historical concentration in these wells is 5 µg/L.	
1,2,3- trichloropropane	11	Wells 02991, 03391, and 07891	1992	None	Maximum historical concentration in these wells is 5 µg/L	

САН	Number of Detects > Reporting Limit Since 1986	Wells with Relatively Large Concentrations	Period of Relatively Large Concentrations	Tier II Action Level (µg/L)	Notes
1,2-dichloropropane	58	Well 07391 and CPT01193	1992- 1993	5	Maximum historical concentrations at well 07391 and CPT01193 were 200 and 100 μg/L, respectively. Maximum concentration during 2003 at well 07391 is 4.9 μg/L
1,3-dichloropropane	9	Wells 02991, 03391, and 07891	1992	None	Maximum historical concentration at all wells is 5 μg/L. ND since 1992
1,3-dichloropropene	ND			None	
2,2-dichloropropane	8	Wells 02991, 03391, and 07891	1992	None	Maximum historical concentration at all wells is 25 µg/L. ND since 1992
3-chloropropene	ND			None	
cis-1,3- dichloropropene	. 16	Wells 07391 and 12691	1992	0.473	Maximum historical concentrations at wells 07391 and 12691 were 1,600 and 13 μg/L, respectively. No detections since 5/12/99 when Well P209489 had 4 μg/L.
Hexachloroethane	12	Wells 18499 and 18199	1999	6.08	Maximum historical concentrations at wells 18499 and 18199 were 179 and 17 μg/L, respectively. Only detected in Wells 18199, 18399, 18499, 18599, 06691. Maximum recent concentration is 74 μg/L in Well 18499.
Hexachloropropene	ND			None	
Pentachloroethane	ND			None	
trans-1,3- dichloropropene	11	Wells 02991, 03391, 06691, 07891, 6287, and 0974	1989- 1992	0.473	Maximum historical concentration in Well 06691 was 8.1 μg/L on 5/19/92. Concentration in wells 02991, 03391, 07891, 6287, and 0974 is 5 μg/L.
trans-1,4-dichloro- 2-butene	ND			None	

## APPENDIX I COMPARISON OF CHEMICAL DECAY RATES VERSUS RADIONUCLIDE DECAY RATES

## Appendix I Comparison of Chemical and Radionuclide Decay Rates

Much can be learned by examining the similarities and differences between the chemical decay rates of CAHs and radionuclide decay rates. The processes and equations describing radioactive decay are well-established (Friedlander et al., 1981). Furthermore, a more mature nuclear literature exists for radionuclide decay than presently exists for CAH chemical/biochemical decay. Important similarities and differences are discussed below.

Based on a century of scientific work, it is well established that radioactive decay follows the first-order decay equation (Section 3.1.2.2 and Friedlander et al., 1981). In comparison, biodegradation of CAHs is usually assumed to follow a first-order decay equation, although real world data may fit other rate equations (EPA, 1998; Newell et al., 2002).

A radioactive decay constant is an intrinsic property of a given radionuclide. Radioactive decay rates are independent of temperature, pressure, and the geochemical environment of the radionuclide. In contrast, rate constants for CAH decay in groundwater are not intrinsic and are expected to vary both spatially and temporally with local environmental factors. Examples of these factors include DO concentration, redox potential, pH, alkalinity, chloride concentration, substrate availability for bacterial growth, and temperature. Biodegradation rate constants for a given CAH vary widely at different VOC-contaminated sites across the United States (EPA, 1999c).

Recent literature regarding determination of decay rates for CAHs usually ignores considerations of the relative half-lives of parent and daughter compounds in decay chains (Newell et al., 2002). Bulk attenuation rates, point attenuation rates, and biodegradation rates are normally estimated from concentration data (plotted versus migration distance or elapsed time) without regard to parent or daughter concentrations.

Radiochemical literature indicates that different concentration versus time behavior may be expected for parent and daughter activities depending on their relative half-lives (or decay constants). Three general types of behavior have been recognized no equilibrium, transient equilibrium, and secular equilibrium. To evaluate these models, Excel spreadsheets were set up based on a solution to the first-order linear differential equation given by Friedlander et al. (1981, p.193, Eqn. 5-2). Prior to setting up the

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spreadsheets, the equation was converted from an atomic (activity) to a concentration basis. The final equation is given below.

$$C_d = P/(D-P) \{ \exp(-Pt) - \exp(-Dt) \} (C_p^o F_d) / F_p + C_d^o \exp(-Dt) \}$$

where:

• t elapsed time in years since time zero "to".

•  $C_d$  concentration of daughter at time t in  $\mu g/L$ .

•  $C_d^{\circ}$  initial concentration of daughter at time zero.

•  $C_p$  concentration of parent at time t in  $\mu g/L$ .

•  $C_p^{o}$  initial concentration of parent at time zero.

• D first-order decay constant of the daughter in units of per year

• P first-order decay constant of the parent in units of per year

• F<sub>d</sub> formula weight of the daughter compound in ug/mole

• F<sub>p</sub> formula weight of the parent compound in ug/mole

• exp indicates exponentiation

The above equation was solved using the spreadsheets for various ranges of parent and daughter decay rates. The calculations assume an initial CT concentration of 5,000  $\mu$ g/L is decaying to daughter CF, which was initially present at a concentration of zero (0)  $\mu$ g/L. The results are shown on Figures I-1 through I-3. The decay constants that were assumed are noted on the figures.

The no equilibrium case occurs when the parent is much shorter-lived than the daughter. That is, P >> D, where P and D are the first-order decay constants of the parent and daughter, respectively. This situation is illustrated by Figure I-1. The parent is observed to rapidly decay relative to the daughter. As the parent decays, the daughters' concentration increases to a maximum and then decreases. A key feature of the no equilibrium case is that the concentration ratio of daughter to parent increases logarithmically after the daughter has reached its maximum concentration. Secondly, note that the total concentration of parent + daughter decays at the daughters' decay rate.

If the parent has a half-life that is close to that of the daughter, the parents' decay constant is, of course, similar to that of the daughter, thus  $P \cong D$ . P and D are the first-order decay constants of parent and daughter, respectively. After sufficient decay time, the parent and daughter concentrations reach transient

equilibrium. Transient equilibrium means that the concentration ratio of daughter to parent asymptotically approaches a constant ratio (Friedlander, 1981). This behavior is illustrated on Figure I-2.

If the parent has a half-life that is much longer than that of the daughter, i.e., P << D, then the parents' concentration does not decay significantly during many daughter half-lives. After sufficient time, the concentration of the growing daughter reaches a maximum and thereafter the daughter/parent concentration ratio is effectively constant. This is called secular equilibrium and is shown on Figure I-3. In this case, the parent is so long-lived that the total concentration of parent + daughter is essentially identical with the parent's concentration.

An important conclusion from Figures I-1 through I-3, is that regardless of the relative magnitudes of the decay rates of parent and daughter compounds, the concentration of the daughter always passes through a maximum concentration prior to decaying towards zero. Therefore, we would expect CAH daughter concentrations in migrating groundwater to pass through a maximum concentration at some point downgradient of the source area. This behavior is shown on the general and Site-specific conceptual models.

Regardless of the relative magnitudes of the parent and daughter decay rates, the elapsed time ( $T_{max}$  in years) to the peak concentration of daughter product is given by Friedlander et al. (1981, p.198) as  $T_{max} = \ln(D/P)/(D-P)$ . Once  $T_{max}$  is known, solving Equation I-1 at  $t = T_{max}$  will yield the peak concentration of daughter.

If a DNAPL source term is not removed, it degrades slowly in relation to the decay rates of aqueous CAHs (Newell et al., 2002). The parent CAH concentration in groundwater is continually replenished by dissolution of the DNAPL. Dissolution of the parent may yield an apparent decay rate that is slower (i.e., has a longer half-life) than its true decay rate in groundwater if the source had been removed. The point attenuation rate constant (Section 3.1.2.3) reflects the rate of dissolution or source persistence over time at wells located within the source zone. It can be used to estimate the time required to achieve a remediation goal or action level at source zone wells (Newell et al., 2002).

Figure I-1 No Equilibrium Case of Parent and Daughter Decay (P >> D)

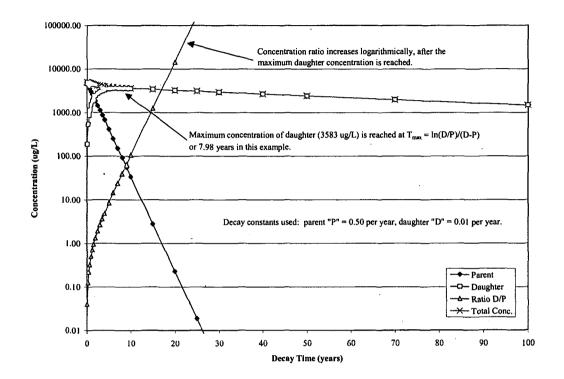


Figure I-2 Transient Equilibrium Case of Parent and Daughter Decay ( $P \cong D$ )

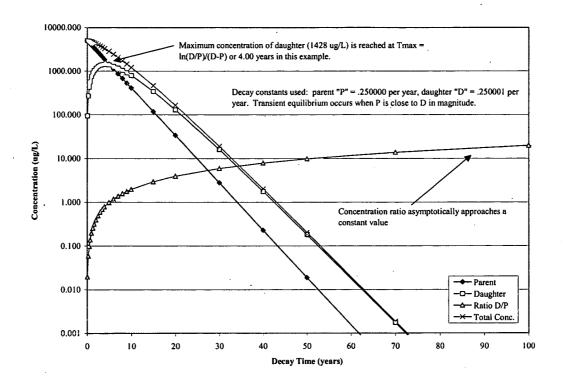


Figure I-3 Secular Equilibrium Case of Parent and Daughter Decay (P << D)

